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ABSTRACT

Recent developments in science and engineering indicate the need for systems approach to problem solving in the widest sense. Following the explication of the concept of a system, the scope of system theory and systems engineering is discussed and operationally defined, with characteristic features of the methodology of systems science and engineering investigated. The state-of-the-art in systems science and engineering education is reviewed. The impact of systems science on engineering curricula, interdisciplinary and intradisciplinary study and research programs and on the structure of academic institutions is discussed. A method for identifying what constitutes the core of systems science and engineering programs, based on the factor analysis of catalogue descriptions of systems science and engineering courses and other relevant data, is proposed. The proposed method is demonstrated and tested on a sample population of such course descriptions, with the model curriculum based on the subject areas in the core being compared with other models of systems science and engineering curricula. The proposed method is also shown as being usable in identifying scope and orientation of academic curricula in general and of systems science and engineering curricula in particular. The feasibility of developing a technique for matching student's background and interests with program orientation is also demonstrated. (Author/PR)

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Pranas Zunde
Georgia Institute of Technology
Atlanta, Georgia 30332

A CURRICULUM STUDY OF SYSTEMS SCIENCE AND ENGINEERING PROGRAMS

April 1972

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE

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Since as yet there is no concensus what constitutes the core of systems science and engineering programs, a method for identifying such a core is proposed. The method is based on the factor analysis of catalogue descriptions of systems science and engineering courses and other relevant data. The proposed method is demonstrated and tested on a sample population of such course descriptions. The model curriculum based on the subject areas represented in the core is compared with other models of systems science and engineering curricula. It is also shown that the proposed method can be used to identify scope and orientation of academic curricula in general and of systems science and engineering curricula in particular. Furthermore, the feasibility of developing a technique for matching student's background and interests with program orientation is demonstrated.

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PREFACE

Developments in curricular and course offerings in the area of systems science and engineering have, in most cases, been evolutionary--stemming from a gradual recognition of the growing complexity of problems of science and engineering and the pressing need for a systems structuring of problem solving approaches. Much useful cross-disciplinary interchange has taken place, and the developments have been most encouraging.

However, systems science and systems engineering do not yet have commonly accepted scope or characteristics. The area can be defined and translated into educational programs, all with considerable justification, from many different points of view, perhaps with widely differing consequences. At this point in time one cannot tell, which approach is most appropriate.

The present study is aimed at providing insight into the various approaches, hopefully to aid in the determination of future directions of development as those concerned with courses and curriculum interpret the results as seems appropriate to them.

It is almost self evident that the role of "systems" is strongly influencing education in almost all areas of science (both "hard" and "soft") and engineering. It is also almost as evident that identification of the essential content of various systems science and engineering programs should be useful.

We hope that the study made some contribution towards the clarification and better understanding of these and related issues.

The study was sponsored by the Office of Education, U.S. Department of Health, Education, and Welfare, and the author gratefully acknowledges this support. He is also very grateful to Dr. Robert N. Lehrer, Director of the School of Industrial and Systems Engineering, Georgia Institute of Technology, for his encouragement and help, especially in the early phase of the project. Mr. Seiichi Fujita, a graduate student at the School of Industrial and Systems Engineering, was actively involved in many phases of this project and contributed significantly to its success. Last but not least, it is a great pleasure for the author to acknowledge the contributions of all those

persons in various academic institutions - too numerous to mention -, with whom the author was in contact either by correspondence or during his visits of the institutions and who generously supplied information so vital for this study.

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CHAPTER 1. INTRODUCTION.

1.1 Recent Trends in Science and Engineering

When one looks at the trends of scientific advancement, one observes, on the one hand, the development--in depth and in breadth--of the traditional scientific disciplines, and, on the other, the emergence of entirely new ones. The emergence of new scientific disciplines is governed essentially by two major factors: (1) a tendency toward *specialization*, and (2) a tendency toward the *generalization* of science.

Increased specialization is caused by the discovery of new areas of research or subjects of study, which stimulates scientific interest in an exhaustive investigation of a relatively narrow class of phenomena. The resulting disciplines are characterized by their specific approach to the analysis and solution of the problems with which they deal; examples of such disciplines are the chemistry of polymers and micro-paleontology.

The tendency towards generalization issues from a desire to determine the general laws of various phenomena in a variety of subject areas. This approach leads to the creation of such disciplines as dimension theory, theory of similarity, theory of dynamical systems, and thermodynamics.

An important specimen of the latter class of emerging disciplines is systems science and engineering. It should be noted that considerable impact on the development of disciplines such as systems science and engineering stems from changes which are taking place in our environment. With industrial, managerial, social, and other real world problems becoming increasingly complex, the engineer and scientist of the "subject specialist" type is gradually replaced by the "problem specialist" who is expected to pull from a variety of disciplines all those techniques which are useful for the solution of a particular problem, and to be able to apply those techniques to the problem's solution. Since the acquisition of such broad knowledge and technical capability is feasible only up to a certain level--even though that level is surprisingly high--, there is an increasing

tendency towards the organization of "work teams", composed of representatives of various disciplines, to cope with complex problems.

The changing emphasis in the scientific approach to problem solving manifests itself not only in new disciplines, but also in the conventional ones. For example, a recent study showed that biologists now favor a classification of their activities according to the levels of organization at which they work, rather than according to their specialties. Thus we have molecular biologists, cell biologists, organ systems and organism biologists, and population biologists. Workers at each level of organization find communication with others working at the same level quite natural--regardless of what variety of lifeplant, animal or bacterial, may be the particular objective of their study. In contrast, communication between workers at different levels of organization is not so easily achieved, and may fail so conspicuously as to lead to misunderstanding or even hostility. [34]

1.2 Systems and the Needs of Society

The trends in science which have been briefly discussed in the preceding chapter are not the expressions of random whims of scientists, but the reflections of very definite needs of the societal development. Thus, legislators and governmental officials are interested in solutions to national problems, planners in developing conutries are concerned with the improvement of the standard of living and so on. They and others in the society are asking for someone or some group to accept the challenge of total system design. Among the kinds of systems obviously in need of such design efforts are law enforcement systems, health delivery systems, educational systems, management systems, traffic systems, public transportation systems, resource management systems, and others.

The question is who should concern himself with such problems? Obviously, no one expects the engineers to usurp the roles of policemen, doctors, teachers, or managers. To quote Wymore [49],

> "the appropriate role of engineering can be seen through the following analogy: do pilots design airplanes? Well, pilots are frequently involved in the design of airplanes; pilots test airplanes; the input of pilots to the design process is important. But, ultimately, it is the engineers who make the design decisions, not the pilots. The pilots turn out to be human components of the aircraft system and their input to the design process is important primarily with respect to the design of the interfaces between pilot and the rest of the aircraft.
>
> Similarly, policemen are components of a law enforcement system, doctors are components of a health delivery system, teachers are components of an educational system, and managers are components of a management system. Still, the system in each case, should be designed by an engineer. Or, to turn this assertion around, he who designs such a system is an engineer whether or not he is also a pilot or more generally a component of the system."

It is being argued that even in traditional engineering there is a strong need for shift of emphasis, especially towards the design orientation. According to Lifson [27], design must become an essential part of the engineering curriculum. In particular, the design stem must emphasize the sequence of activities comprising the design process. For the engineer to be able to integrate mathematics, science, and the humanities in the identification of an optimal system, he must be able

to implement the design process as an entity--including value modeling, evaluation, optimization, and decision, as well as the more familiar synthesis and analysis.

In line with the above, Lifson has the following to say about the impact of systems-related developments on society [27].

> "Advances in science, mathematics, and computing technology have enabled man to synthesize and analyze increasingly complex systems. Historically, intuition and subjective judgments have been the direct, primary basis for decisions concerning system concepts and system requirements during the initial planning phase of the system life cycle. Today, operations analysis techniques and systems engineering increasingly permit explicit, quantitative identification of optimal system requirements.
>
> The resulting increasing interdependence of technology and policy (in both private enterprise and government), ..., the frequency with which innovative, large-scale systems have significant impact on international relations, on the national economy, on our social structure, and on the financial health of individual corporations cannot be ignored. Top level management planning decisions are increasingly and inherently technology-based. Our space program, the Department of Defense, the aerospace industry and, increasingly, state and local governments are basing policy decisions on technological factors. The implications of this injection of technology into planning and management means that engineering education can neglect neither the initial planning phase of the system life cycle nor the management of complex systems if it is to be responsive to the needs of society."

In some fields, such as in various areas of modern management and organization, the contributions of research methodology and management science to the solution of business problems have grown rapidly enough in recent years to be almost traumatic to present managers. The contributions of research methodology were primarily in the application of scientific methods of search, measurement and verification as contrasted to intuition based on convenient data, whereas management science concentrated on the application of research results through analysis and synthesis, and the development and verification of systems models for the solution of business problems. It has been primarily because of the optimization techniques of management science that the business firm has come to be regarded as a system rather than a collection of isolated problems [31]. Nonetheless, a lot remains yet to be done.

1.3 Objectives and Methods of the Study

The objectives of this study of the academic curricula in systems science and engineering and of their trends of development were manifold. Even though the study was motivated by practical institutional needs, it is felt that the subject matter covered in the study and the methodology applied should be of interest to the whole academic community. Specifically, the major objectives of the study were:

1) To survey the existing academic programs in systems science and engineering in the U.S.

2) To investigate the basic philosophy and subject matter orientation of these programs.

3) To clarify the concept of systems science and engineering as an academic discipline.

4) To identify the common core of existing systems science and engineering curricula.

5) To evaluate the existing systems curricula and courses in terms of the common core.

6) To clarify the relation of systems science and engineering program to other academic disciplines.

7) To develop a tool for systems engineering curriculum improvement.

8) To design a testing procedure for the identification of student interests in systems science and engineering programs and for student orientation.

A few words follow about the scope and type of data which was collected for this study and how it was applied to this study. The study was implemented in phases as follows:

- Requests for information were sent to all academic institutions which were considered likely to have a Systems Science and/or Engineering Program.
- After reviewing the responses to the first requests, academic institutions which had relevant programs were selected and analyzed in greater detail.
- Using the catalogs of the institutions and other available information about the programs, in particular information obtained during the site visits, a list of institutions

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with Systems Science and/or Engineering Programs was composed.

- The descriptions of courses in selected programs were put in machine readable format and processed using a specially developed computerized analysis program for identifying the major factors represented in the courses.
- The programs and courses were evaluated in terms of the extracted "common core" of the systems science and engineering curricula.

The model curriculum thus obtained was analyzed and compared with other proposed designs of systems science and engineering programs. The proposed methodology seems to be applicable not only to the analysis and evaluation, but also to the modular design of programs in any academic subject area.

CHAPTER 2. SYSTEMS THEORY AND ENGINEERING

2.1 Explication of the Concept of a System

Before addressing ourselves to the question of the nature of systems theory and engineering, we need to explicate the concept of the system itself and to explain the difference between real systems and their mathematical or other models.

Assume that one is concentrating his attention on some computational procedure, or a telecommunication device, or a social event, or on any other physical or non-physical phenomenon. One recognizes a system in the matter under consideration if one is able to identify a family of objects and, furthermore, discovers (or asserts) that these objects are interdependent. Hence, regardless of the specifics of the matter involved, one can say that, first of all, a system is a family of interrelated objects.

Introduced in such a broad context the notion of a system is apparently a constant companion is everyday experience. Examples are abundant. Take an electrical d-c machine. It becomes an electrical system if one identifies a family of so-called electrical variables (e.g. the excitation voltage, the excitation current, the induced e.m.f., the armature resistance, and the output voltage) as the objects of interest and, furthermore, one acknowledges the existence of a relation between them. On the other hand, starting with the same d-c machine, one can identify an electro-mechanical system by taking as the objects another set of variables (e.g. the mechanical torque, the rotation speed, the armature voltage and the armature current). Still further, one can recognize an economic-technological system by taking as variables the per unit cost of providing the d-c machine (generator) with the required power, the output voltage, and the cost for keeping the output voltage at a given level or penalties for deviation from that level.

Apparently, many different systems can be associated with given phenomenon or, to put it differently, given phenomenon can be described as a system in many different ways.

Given two systems S_1 and S_2, one of them, S_2, for example can be considered as the model of another, e.g. S_1, if their behavior is the same (equivalent) in a given sense. In other respects the systems S_1 and S_2 might be very different. To make the model useful, the model system should be considerably simpler in all other non-relevant aspects, or at least should be much better understood.

Either system or model or both can be physical or abstract systems. Of particular importance in sciences and engineering are the abstract, mathematical models. An abstract mathematical model is a set of mathematical relations such that the properties of these relations correspond to the respective properties of a real system. These models are specially important because they offer a basis for making some definite statements about the bahavior of the real systems; statements which can be verified by using the scientific method.

The above explications of the concepts of system and model were proposed by Mesarovic and quoted here practically verbatim.

Although other definitions vary considerably with respect to the degree of generality, they do have certain things in common. For instance, Eldin defines a system as

> "an array of components designed or organized to accomplish a particular objective according to plan or to constrain action toward a specified end; a collection of operations and procedures, men, and machines by which business activity is carried on." [15]

Affel extends the definition of a system to complex entities wherein there is a set of user requirements that can be met only by a large number of interrelated functions which collectively are beyond the scope of any one engineering discipline. Consequently, a system problem is integrating all of these disciplines in an optimum fashion, so that the output of the system would meet the stated need [1].

In a similar vein, Lifson and Kline define a system as a set of resources organized to perform a set of designated functions in order to achieve desired results. The resources include personnel, material, facilities and information. The system is imbedded in a set of environments--physical, social, political, economic, and technological. These environments comprise a super system with which there are strong, highly

complex interrelationships. These environments are a source of information and constraints concerning the use of the system, and of technology which must be considered in the design, development, and operation of the desired system [27].

In a paper presented at the Annual Meeting of the American Society for Engineering Education in June, 1968, Robert W. Braswell, Professor and Chairman of the Industrial and Systems Engineering Department of the University of Florida, explicated the concept of a system in operational terms as follows:

> "A system is an integrated assembly or orderly compilation of elements (components) designed to carry-out co-operatively a predetermined function (practical concept). One can visualize the most nearly perfect system, the human body. The Apostle Paul when describing the Church said 'But now are they many menbers, yet but one body'. St. Paul was describing a form of social system with a theological objective. Whether one is analyzing and/or designing a social, procedural, hardware, process, tracking, computer, education, transportation, or management system, there are common factors; all of them have parameters, variables of interest, and objectives.[9].

As a final example, we shall quote an operational definition of a system by T. A. Morton.

> "The Systems Engineering method recognizes each system as an integrated whole even though composed of diverse, specialized structures and subfunctions. It further recognizes that any system has a number of objectives and that the balance between them may differ widely from system to system. The methods seek to optimize the overall system functions accordingly to the weighted objectives and to achieve maximum compatibility of its parts."

It can be readily seen that all these definitions associate with the concept of a system the following main attributes:

(i) complexity in terms of interacting components, and

(ii) functionality or purposefulness.

Consequently, we shall adopt the following definition: *A system is a complex entity of interacting components serving a specific function or goal.*

2.2 The Nature of Systems Theory

Prior to analyzing educational programs in systems science and systems engineering, we shall ask the question what is the proposed scope and nature of these disciplines.

Although the need for preoccupying oneselves with things which are referred to as systems is generally recognized, i.e. even though it is generally agreed that systems research, systems analysis and systems design is an important part of modern technical and scientific development, we are still far from an agreement whether or not there is such a body of knowledge as *general systems theory*. In other words, there is no concensus in the scientific world that what some scientists call general systems theory is indeed a well developed branch of science and even less agreement as to what is the domain and scope of such a theory.

One of the early proponents of general systems theory, Ludwig von Bertalanffy, argues that one of the main tasks of general systems theory is the exposition and explication of structural and behavioral isomorphisms of various classes of systems [47]. For example, the negative exponential law can be applied to radioactive decay, to the breakdown of a chemical compound in monomolecular reaction, to the death of bacteria under the influence of light or disinfectants, to the consumption of an animal by starvation, and to the decrease of an animal or human population where death rate is higher than birth rate. Analogies of this type could be the empirical foundation for the development of theory.

Hempel, on the other hand, questioned the value of such disclosures of isomorphisms of systems for the construction of a theory. In his opinion, the recognition of isomorphisms between laws does not add to, or deepen the theoretical understanding of the phenomenon in the two or more fields concerned. Much understanding is accomplished by subsuming the phenomena under general laws or theories, and the applicability of a certain set of theoretical principles to a given class of phenomena can be ascertained only by empirical research, not pure system theory [20].

The differences of opinion between the supporters and critics of

general systems theory have been very aptly described by Boulding [7]:

> "The general systems man is the sort who would be reminded of Pittsburgh even in the middle of Bangkok, simply because both are cities and have streets with people in them. The critic (I somehow visualize him as a historian in a high collar) has a passion not so much for order and tranquility as for feelings that are peculiar, unique, strange, and disjoint. As a general systems man, I will visit him in his lonely eyrie, but even there I will probably be reminded of something--much to his annoyance. To avoid circumlocutions, let me call my general systems man a generalist and my high-collared historian a particularist. The generalist rejoices when he sees, for instance, that in all growth patterns there are significant common elements, such as nucleation, structural adjustment in the part of the system, diminishing returns to scale, and ogive curves. A particularist brushes this aside and rejoices in the fact that the growth of the flower is so different from the growth of a crystal, or the growth of Rome is so different from the growth of Athens."

There also exists an unusually broad spectrum of opinions with respect to the scope or coverage of the general systems theory. In this respect systems theory has been identified with the theory of control, filtering and information; generalized network theory; the theory of optimization; the theory of finite systems or, more generally, the application of discrete, finitistic methods of mathematics; the theory of physical systems taking into account economic (i.e. non-physical) aspects of the systems' operation; the theory of man-machine complexes; the theory of systems which involves humans as elements or, perhaps, consist exclusively of humans; or, finally, the theory of the "systems approach" (systems methodology) whatever that "approach" happens to be [30].

In the opinion of Ludwig von Bertalanffy, who takes a very broad view of the subject matter, the areas of direct interest to the general systems theory are [4]:

Cybernetics, based upon the principle of feedback or circular causal trains which provide mechanisms for goal-seeking and self-controlling.

Information theory, based on the concept of information as a quantity measurable by an expression isomorphic to negative entropy in physics and concerned with developing the principles of its transmission.

Game theory, concerned with rational competition between two or more antagonists for maximum gain and minimum loss.

Decision theory, concerned with rational choices within human organizations and based upon examination of a given situation and its possible outcomes.

Topology or relational mathematics, including such fields as network and graph theory.

Multivariate analysis, i.e., the application of mathematical analysis to the isolation of factors in multivariable phenomena.

R. E. Kalman refers to general systems theory as the study of those properties of the system which differ substantially from the properties of the components of the system. Mesarovic defines general systems theory to be a theory about mathematical models of real life systems such that the essential properties of these systems are revealed using a minimal mathematical structure [30]. He maintains that within the framework of such theory, two types of problems are of major importance, namely

Constructive specification: How to provide an efficient procedure for use in prediction, i.e., to determine some of the elements of the system when some other elements are given. As a basis for predicting the systems behavior, the concept of constructive specification is essential for the utility of the systems notions.

Systems properties: How to formalize certain properties of interest in the characterization of real-life systems and how these properties are related with constructive specification.

Mesarovic further suggests that considerable clarification regarding the essence of systems theory can be achieved by being careful to distinguish real systems and the nature of their constituent components (and the meanings attached to them) from formal abstract descriptions of the behavior of these systems. For example, two different real systems, one consisting of a human, another of electro-mechanical components can behave "the same" in the sense that the same mathematical model can be used to describe certain aspects of the systems behavior. The objective of systems theory is to further the under-

standing of the behavior of real systems by analyzing the formal mathematical models and only indirectly to improve the tools of analysis or synthesis [31].

To explain the importance of and the need for the systems theory in both the sciences and in engineering, Mesarovic draws a parallel with the methodology in experimental fields. Thus [31]:

> "It is generally necessary that an experimenter have at his disposal a large variety of instruments which he can use as the situation requires. Somewhat analogously, to build a theory from experimental data, a theoretician should possess the knowledge of a wide class of different models. In the initial and by far the most crucial stage of the development of a theory, the theoretician has to select the appropriate abstract system to be the model for the real system. Apparently, he can do this only if he has a rich-enough repertoire of models. Formal systems theory is devoted to make such a selection easier by describing and classifying different abstract models."

If the subject matter of systems theory is approached in the above vain, then

> "The systems under consideration are mathematical models of real or conceptual systems and systems theory then consists of statements about these mathematical models; second, the statements in the theory are mathematical and refer to the formal properties of the model, i.e. express how the objects are related rather than what specific menaing or interpretation they might be given. The theory is then apparently valid for any system which can be modeled by the given model. This is the principle reason why the formal theory of systems is of such importance. By developing a theory of an abstract model, one has a theory of formal behavior of any conceivable system which can be modeled in the given way. It is only natural then to take the formal theory of models as a unifying theory in sciences and engineering."

In summary, there exists a large spectrum of ideas on what constitutes systems theory, some of these being conflicting. On the other hand, many traditional and well-structured scientific disciplines are not clearly defined in scope either. Since the scope of systems theory must by necessity be very broad and comprehensive, staking out the precise boundaries of the subject area must become a controversial problem. The effect of this on the development of the discipline does not have to be negative, and in this case there is indeed no indication that the controversy does affect the growth of the discipline. On the

contrary, it seems to stimulate it rather vigorously, especially in the areas of overlap with other disciplines.

In engineering, systems theory is of particular importance where one has to deal with real systems phenomena from different disciplines or where one has to deal with complex socialogical, economic and other systems in which emphasis is placed on decision making and information flow. These problems are generally considered as belonging to the domain of systems engineering. And if these were the only problems of concern then it would be correct to say that systems engineering is the application of systems theory to interdisciplinary engineering problems.

2.3 The Nature of Systems Engineering

It is interesting to note that the emergency of systems theory reflects an evolutionary process in the engineering field brought about by the ever-increasing complexity of engineering problems. Consider, for example, electrical engineering. The problem of the interconnection of electric machinery at the turn of the century resulted in the notion of a generalized electrical machine. This, depending upon the selection of parameter, can represent any of a class of machines. Subsequent developments required the concept of an equivalent electric circuit which can represent both stationary as well as rotatory systems. Still later, the notion of generalized network has been developed to deal with the problems involving different physical phenomena. Finally, when problems involved some aspects outside of the domain of physical laws (e.g. economics), the concepts and the field of systems theory emerged [30].

Whatever may be the assumptions regarding what constitutes systems theory, systems engineering can be properly defined as the application of that theory to engineering problems. Unfortunately, this was not the underlying logic of the historical development of the relationship between systems theory and systems engineering, and it is not uncommon to encounter explication which do not postulate that systems theory must be a prerequisite for the development of systems engineering.

It is quite popular to explicate the concept of systems engineering by contrasting it with that of component engineering. Thus Eldin writes [15]:

> "A *systems engineer* is defined as 'one whose practice of engineering disciplines is uniquely associated with systems.' In practice, the systems engineer is the coordinator of the team composed of the many parts of the system. An engineer becomes a systems engineer rather than a component engineer when his scope acquires a certain integral quality, wherein he recognizes not only the internal structure but also the structure of the total environment of the problem.
>
> This definition warrants a clear differentiation between *systems* and *component engineering*. Although the system-component distinction is an individual decision, most participants seem to agree that when the individual items in a project cover a wide spectrum of disciplines, the project warrants the designation of *engineering system*. The

individual items are really components, and *component engineering* may be applied to the individual subsystems, even though they may be substantial systems in their own right.

Systems engineering is defined as 'a process for establishing significant objectives, for allocating resources, for organizing information so all aspects of a problem may be known as exactly as possible, and for providing the coordination between process, people and tools to achieve stated goals according to a predetermined schedule.' The process provides for a bridge between what is needed and what is feasible and economically practical. It makes provisions for reaction to deviations of actual results from predicted performance to prevent development of an undesirable situation."

One of the main objectives of systems engineering is seen to stem from the fact that in the latest development of technological society, undesirable results often can no longer be tolerated, and therefore it is necessary for some engineering function to consider all the essential factors associated with any project or industry and provide not only the desired results but also means for remedying undesired effects that accompany them. This means that the engineering approach to this type of problem should concern all essential inputs, all significant outputs, and all of their interactions. Since engineering has always been concerned with interactions among some set of inputs and their associated outputs, -- even though the level of complexity was much lower and the side effects of the problem solution usually could have been neglected --, systems engineering is viewed by some people as only a rational development of engineering as it has been practiced for centuries [14].

Indicative of the prevailing views on what constitutes systems engineering are also the definitions used in the manuals, guides, and procedures of modern industrial enterprises, government agencies, armed forces etc. Extracts from the documents of three such organizations are reproduced in Table 1 (adopted from Ref. 22). Having analyzed a variety of operational definitions of systems engineering of this kind Howard summarized the main underlying assumptions as follows:

. Design is the core and essence of engineering.

. The essence of systems engineering can be found in the

Table 1. Selected System and Systems Engineering Definitions

NASA Documents	Army Documents	AF Documents
System One of the principal functioning entities comprising the project hardware and related operational services within a project or flight mission. Ordinarily, the first major subdivision of project work. (A system may also be an organized and disciplined approach to accomplish a task; e.g., a failure-reporting system).	*System* A composite of equipment, skills and techniques capable of performing and/or supporting an operational role. A complete system includes all equipment, related facilities, material, software, services, and personnel required for its operation and support to the degree that it can be considered a self-sufficient unit in its intended operational environment. The system is what is employed operationally and supported logistically. It is the product of the acquisition program.	*System* A "system" is "a composite of equipment, skills, and techniques capable of performing and/or supporting an operational role."
Systems Engineering The process of applying science and technology to the study and planning of a system so that the relationships of various parts of the system and the utilization of various subsystems are fully established before designs are	*Systems Engineering* The selective application of scientific and engineering efforts to (1) transform an operational need into a description system configuration which best satisfies the operational need according to the measure of effectiveness; (2) integrate re-	*Systems Engineering* All parts of a system must work together and have a common unified purpose; namely to contribute to the production of a single set of highest outputs based on given inputs. This absolute necessity for coherence requires an organization of creative technology

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Table 1. Continued

NASA Documents	Army Documents	AF Documents
committed. [32]	lated technical parameters and assure compatibility of all physical, functional and technical program interfaces in a manner which optimizes the total system definition and design; and (3) integrate the efforts of all engineering disciplines and specialties into the total engineering effort. [44]	which can lead to the successful design of a complex military system. This organized creative technology is called "system engineering." [2]

creative process of formulating and structuring systems, methodically organized and managed under central control, and interacting with all the required disciplines and constraints for the design of that particular system throughout the system life cycle.

. Systems engineering is fundamentally concerned with deriving a coherent system design to achieve stated system objectives.

. One of the most important concepts of modern times is the systems approach, which attempts solutions of complete problems, in their total environment, by systematic assembly and relating of parts to solve the whole problem in the context of the life cycle of the system, and considering all relevant aspects.

. Successful planning and acquisition of large complex systems as solutions to recognized problems <u>requires</u> the "systems approach."

. In its application, the systems approach requires that the solution to the problem be planned and acquired as a total entity to satisfy the requirements of the user.

. The systems approach recognizes the interrelationships and dynamics which tie a system together to achieve stated objectives; and recognizes that factoring out parts of the problem by neglecting significant relationships, interactions or aspects of system elements and components increases significantly the probability that the solution to the problem will not be found.

. In its implementation, the systems approach requires the application of a rational methodology, which is the most characteristic feature of systems engineering.

. A pattern of events and activities can be observed and identified in the development of engineered systems, which are repeated from system to system through the life cycle of the system.

. An "engineered system" is a system planned and developed through deliberate and explicit application of the systems approach.

. Since systems engineering is the application of the systems approach, and since each phase of the system life cycle includes the design process, combining the life cycle with the design process provides an operational description of systems engineering; provides a rational basis for the allocation of resources, for identifying the flow and transformation of information, for describing the process which engineering managers must manage; and provides the structure and organization for the design of an engineering curriculum [22].

Reasoning along these lines, Howard drew the conclusion that system engineering is a way of approaching complex problems and organizing their solution on a timely and cost-effective basis -- i.e. it is a methodology, a process. It addresses itself to the total system complex, interrelating all the elements, hardware, personnel, procedures, facilities, support and cost-effectiveness, with a view to arriving at more integrated solutions to the multiple interrelated system problems.

2.4 Demand for Systems Engineers

Several independent studies were recently made to identify what are the needs for systems engineers in government and industry, what qualifications they are expected to have, what are the problems they are expected to work on etc.

In some branches of the government, the sytems approach is well known and documented, and specifications are available giving job discriptions and required qualifications for systems people. The National Aeronautics and Space Administration and the Department of Defense have a series of manuals and specifications that cover all phases of the system life cycle from conceptual phase, to definition phase, to acquisition phase, to operation phase.

In the Department of Defense most of these developments were initiated during the McNamara era in DoD. This was a new emphasis on planning for the entire military establishment -- in terms of missions, forces, and weapon systems -- focused on outputs rather than inputs. It introduced the concept of evaluating alternatives and trade-offs, and it related resources to military capability, missions or national objectives. It became an integrated process of planning-programming-budgeting for the Agency, i.e. an integral part of the Agency's decision process. [19,30]

NASA's interest in systems design even extends to the training of new people (usually engineers) who will be doing the systems design of the future. The largest part of NASA's budget is devoted to space engineering rather than space science. Yet, there has always been a shortage of persons who can conceive, design, and develop the complex systems demanded by the new technologies. A spacecraft systems designer must consider structures, materials, fabrication techniques, shock and vibration loads, fuels, propulsion, and aerodynamics, reliability and quality control, space vacuum and thermal environments, instrumentation and testing techniques, safety, operations, and costs; he must also be able to deal with schedules, manpower needs, management-labor relations, budget and fiscal questions, proposals, bid evaluations, and government-contractor relationships. [19]

In the federal government, an important step was taken by President Johnson on August 25, 1965, when he announced a new planning-programming-budgeting (PPB) system to be applied throughout the government. As announced by the President, it will:

> "1. Identify our national goals with precision and on a continuing basis;
>
> 2. Choose among those goals the ones that are most urgent;
>
> 3. Search for alternative means of reaching those goals most effectively and at the least cost;
>
> 4. Inform ourselves not merely on next year's cost, but on the second, and third, and subsequent years' cost, of our programs;
>
> 5. Measure the performance of our programs to insure a dollar's worth of services for each dollar spent." [12]

It should be noted that some of the most progressive industrial corporations have been doing this kind of long-range planning for some time. A study reported by Eldin addressed itself to the question what are the essential qualifications of the systems man in government and industry. There was a surprising agreement among the respondees on this point. It was recognized that the breadth and complexity of problems facing the systems man needs a wider variety of analysis techniques than any single discipline is in the position to handle, in addition to overall synthesizing capabilities. Specifically, it was found that a systems man needs the following qualifications:

. He must have high analytical ability.

. He should be an expert on the methodology needed for systems work, and he must be up to date on the technologies used in system improvements and implementation.

. Although he is not an expert on tools and techniques, such as queuing theory, information theory, etc., he should be familiar with the principles of how to use them in terms of inputs they can accommodate, the relationships they can handle, and the outputs they can produce.

. He must be able to communicate with the specialists in these techniques from other disciplines. [15].

With respect to the demand for systems engineers and specific capabilities which government and industry associates with various facets of a systems engineer's work, interesting results were obtained in the course of a study conducted by a group of students under the

directions of Prof. J. M. Apple at the Georgia Institute of Technology, Atlanta, Georgia. The investigators analyzed job advertisements for systems engineers, covering all media, the entire U. S., and a time space of 2-3 years, and tabulated what abilities, qualifications, etc. were specified for the advertised positions in the field. The results of the survey are listed in Table 2 with the numbers indicating the frequency of occurence of a particular description in the sample population. They can be approximately classified into the following categories, ranked by demand in percent of the sample population.

Area of Specialization	Demand
Production Control and Planning	18.3%
Management Information Systems	16.9%
General Systems Analysis and Design	13.4%
Facilities Design	13.4%
Mathematical Analysis Techniques	12.1%
Information Storage and Retrieval	11.4%
Inventory and Maintenance Control	9.0%
Work Simplification	3.6%
Miscellaneous	1.9%

Table 2. A Survey of Job Advertisements For Systems Engineering

Descriptors used to denote abilities and qualifications needed by applicants for jobs and their frequency of occurence in the sample population.

Advanced integrated systems	1
Air-water pollution systems	2
Applied EDP processing	5
Applied mathematics	1
Business data systems	4
BTAM	1
Clerical systems analysis	3
COBOL	4
Collecting, analyzing, evaluing & reporting information	3
Computer facilities planning	4
Computer programming	5
Computer systems	3
Cost control	8
Cost estimating	2
Cost reduction	3
Cost schedules	2
CPM	2
Data processing	3
Economic analysis	3
Engineering economy	4
Equipment analysis	4
Experimental design	2
Facilities utilization	3
Feasibility	1
File organization concepts	3
Flight mechanics	1
Forecasting	1
High speed conveyor systems	6
Hospital systems	1
Human factors	2
Incentives	1
Input/output analysis	1
Inventory analysis & control	21
Job evaluation	6
Linear programming	5
Management communications	5
Management information systems	12
Manufacturing management	3
Maintenance control systems	5
Market Research analysis	1
Materials handling	14
Materials management	5
Math Models	1
Mathematical analysis	2
Methods engineering	14
Monitor & display systems	1
Monte Carlo techniques	1
Non-linear programming	1
Numerical control machines	1
Office layout	4
Operations analysis	3
Operations research	5
Organization analysis	9
Paper flow	5
PERT	1
Physical distribucion systems	2
Plant layout	9
Probability	3
Process control	4
Production automation systems	1
Production control	10
Production logistics systems	1
Production planning	5
Production scheduling	1
Project/program control	4
OTAM	1
Reporting systems	4
Scheduling	3
Shop loading	5
Simulation	7
Systems analysis	8
Systems design	10
Systems planning	7
Time series planning	3
Tool control	3
Work measurement	5
Work order control	3
Work simplification	4

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CHAPTER 3. SYSTEMS SCIENCE AND ENGINEERING EDUCATION

3.1 Views on Systems Science and Engineering Education

It has been pointed out that the impact of advanced technology on human development results in activities that in modern times cannot be accepted or rejected at will. At the same time events have forced technology and engineering toward levels of complication and size that were unheard of only a few years ago. This leads Wymore to the conclusion that [49]:

> "Students working toward professional careers in technology and engineering must acquire special skills and capabilities to cope with problems of complex systems analysis and design. Whereas industry has the responsibility of providing the systems man with continued growth in his field, the school should supply the necessary foundation on which he can later develop his practical education. In particular, engineering education cannot ignore the necessity that complex systems must be designed and operated, and the responsibility clearly belongs to engineering education. If engineering education abrogates this responsibility, then whoever accepts this responsibility is engineering education, despite what the labels may say."

It is being also argued that most of the failures associated with technological progress are due to poor systems engineering, not to poor device engineering [12].

Compatibility with the needs of society requires, therefore, that engineering graduates have the following capabilities:

- Engineering graduates should be able to extend the application of the design process to the initial stages of the system life cycle (i.e., to the planning phase).
- Engineering graduates should be able to extend the application of the design process to the planning and engineering of complex socio-economic systems such as transportation, health care, housing, waste control, information, and education.
- Engineering graduates should be able to manage the planning, acquisition, and use of complex systems.

Engineering education should play a definitive role in alleviating this situation by including more systems engineering in the curriculum, not just as formalized courses but as an integral part of existing courses. In fact, some would maintain that only upon permeating all of the engineering curriculum with "systems thinking" will there be a chance of developing the professionalism required to

accomplish the task. Toynbee has commented [43]:

"The conventional acedemic dismemberment of a vast subject into disciplines is a convenient, and perhaps unavoidable, educational device, but it is an arbitrary surgical operation, and this makes it a serious impediment to the gaining of knowledge and understanding. It is true that any one mind can make itself familiar with no more than some patch of the great forest. Yet, unless it also dares to venture out into the surrounding stretches that, for it, happen to be terra incognita, it cannot hope to understand the nature even of its own narrow beat."

In a similar vain, Bode has pointed out that in many engineering successes [5]:

"...the basic systems analysis was done by men who had already spent several years in the same or related fields. They were thus in a sense professionals, qualified through subject matter knowledge as well as systems understanding.

I believe that this is the inevitable pattern for any effective attacks on our well-known problems - transportation, environmental control, and so on. At first, the visiting systems engineer with no substantive knowledge of the field ... may be able to make a contribution. As the field develops to the point where sustained intellectual hard work is necessary, however, the men who have developed a sort of professionalism because they work in the area continuously will be increasingly the men who count. They may or may not call themselves "systems engineers," but they are in any case the men who understand the field in enough depth to give it structure and continuity.

In the long run then, the country's future on these problems will depend on finding ways of developing such professionalism. My point here is that this sort of step ... is a requirement for serious attempts to address ourselves to the country's largest problems."

Although there seems to be a general consensus as to the need of a special type of education necessary to provide better insight into theoretical and technological aspects of systems analysis and design, there is also an apparent lack of agreement among practitioners of systems science education as to the content of systems science and engineering programs.

One of the earliest promoters of systems engineering education was M. E. Salveson who defined systems engineering in his paper "Suggestions for Graduate Study in Operations Research and Systems Engineering" as a process in which complex systems are identified, designed and manipulated by conscious rational processes based upon the scientific

method [38]. He proposed a core program in systems engineering consisting of the following bodies of knowledge:

1. Phenomena of the real world comprising such aspects as physics, chemistry, phychology, economics and language;
2. Socially and individually imposed boundary conditions, e.g., history, human engineering, philosophy, and ethics;
3. Symbolic systems for manipulating ideal systems, e.g., logic, game theory, probability and statistics, measure theory, and calculus of variations;
4. Systems of analysis applicable to specific phenomena, e.g., usual engineering courses, information theory, network analysis, theory of information processing;
5. Phenomena of organized human endeavor, e.g., organization theory, group decision theory, creativity, value theory, and group motivation.

In 1957, Lynch discussed early thoughts on a proposed electrical engineering curriculum based upon a systems philosophy to provide fundamental training in all areas of the field [29]. The program outlined was the basis of the present program at the Polytechnic Institute of Brooklyn which will be discussed in detail later.

Ramo defined the role of the fundamental scientist on a system team including experts in many fields [36]. Warfield called for a new approach to education to produce engineers competent in a number of scientific disciplines [48]. He contended that effective measures to improve systems science skills were universal application of functional and detail block diagrams and more effective use of technical writing.

Also in 1958 Thal-Larson made the point that objectives for instruction in systems engineering are to develop an awareness of the properties and interactions of components, and to develop students' abilities to use mathematical techniques [41]. The program he discussed included closed-loop automatic control systems and basic instrumentation, analysis of typical physical systems, block diagramming, and servomechanism theory. He reviewed instructional techniques designed to cope with probelms involved in teaching systems engineering. The course described was taught at the University of California.

Diverse arguments for a distinct and separate systems engineering program were profferred also by Chorafas, Kosavan and Myers, Huggins and others [11,24,25].

More recently, in a paper presented at the Annual Meeting of the American Society for Engineering Education in June of 1968, Robert N. Broswell, Professor and Chairman of the Industrial and Systems Engineering Department of the College of Engineering at the University of Florida, expressed the following views on system engineering as an academic discipline [9]:

> The systems engineers must be very interdisciplinary in both analysis and design, which is precisely the point. No engineering discipline, alone, has the total design capacity for transforming modern scientific discoveries to practical use. The systems engineer bridges the gap; he is first an engineer with a design orientation and with a good kit of interdisciplinary tools. On the other hand, he is also an analyst drawing upon such modern techniques as decision theory, and control phenomena. He does not treat the system parameters with traditional deterministic methodology. Through probability theory and computer simulation, the systems engineer strives to develop meaningful design trade-offs considering the environment and variable behavior. The systems engineer faces disorder on both sides of the gaps; the user requirements are poorly expressed and seemingly disorganized while the complex set of needs have no real order.
>
> Our society is such that people aspire to do more complex things. For all of these complex things, there are complex sets of solutions from which the systems engineer chooses. From a technological viewpoint, most of the individual parts or sub-sets are available to perform the individual functions. As an example, we have automobiles, busses, trains, helicopters, etc. to transport intra-city passengers. We can develop the engines and build the bridges that help us to negotiate terrains, chasms, and streams. Yet, we have not developed adequate urban transportation systems for our nation's needs. When we quit addressing the problem of how to increase the speed and/or capacity of the locomotion, and put our solution strategy to work on how many people want to go from here to there, how long will they be willing to travel and at what cost, we will start utilizing the first facet of the systems engineering process. The systems engineer deals directly with the human environment and is concerned with the consequences of the new operational system once it is built and put into operation. The user must be satisfied with both system utility and long range economics.

Reasoning essentially along the same lines of thought, Wymore suggests that systems science and engineering education should serve the following objectives [49]:

- To produce a systems engineer conditioned to accept the responsibility for the total system design, however that system might be defined by his client;
- To produce a systems engineer at home in many sciences and technical disciplines, a technological linguist who speaks many languages;
- To produce a systems engineer with background and attitude by which he will be able to pick up independently the knowledge he needs rather quickly;
- To produce a systems engineer prepared for survival as an engineer in a rapidly changing technology;
- To produce a systems engineer well grounded in mathematical system theory, and any other scientific or mathematical discipline appropriate for attacking design and analysis problems involving "hardware," man/machine, man/man, and system/society interfaces.

In a memo to the Graduate Group Committee in Systems Engineering, Arthur D. Hall of the Moore School of Electrical Engineering at the University of Pennsylvania made the following comment on an advanced program in systems engineering [18]:

> Any good systems engineering master's degree program should enhance the bachelor's capability to perform design work in his chosen field of technology. In addition, it should provide him with tools and models, which experience shows are encountered in all applications work. Thus, if an electrical engineer wants to become a systems engineer in the field of information handling systems, he will need more knowledge of end instruments (sensors and effectors), computers (or switching machines) placed in the nodes of information handling networks, and communication (or transmission systems) which tie together the nodes and the nodes with end instruments. If we accept Wiener's notion that all systems may be considered information handling systems, with materials handling and energy handling appearing in distinctly subsidiary roles, it follows that any program in Sy.E. should have material devoted to all three major subsystems.
>
> In principle, a Ph.D. Program in Systems Engineering should permit some specialization in any kind of system. However, by definition, systems engineering means capability with respect to many kinds of systems, so that one must search for a reasonable basis for conveying both broad capability and a suitable degree of specialization. The Ph.D. Program, would, therefore provide greater depth in the three classes of subsystems of information handling systems, their design and their technology. For this there would, of course, need to be a new course in sensor and effector (transducer) design and technology. New courses also are implied to convey the general functions and techniques

of material conversion and flow systems, and another to contain the principles of energy conversion and transmission systems. Other courses from which Ph.D. candidates might choose would include linear systems analysis, queuing theory, reliability systems analysis, market research and sampling, R and D management and organization theory, finally case and/or project work in systems design and modeling.

Addressing himself to the goals of graduate education in the systems area, too, Lifson-Kline underscored that the engineering curriculum for professional graduate programs should focus essentially on the preparation of students to perform design, development and other activity in the production of engineering works. Such programs should place major emphasis on design for economic performance, on engineering management, and on society-technology interactions [27].

Specifically, they proposed two types of graduate programs, i.e.

1. An application of systems engineering methodology to the solution of a significant design problem.
2. Research in depth into the activities, tools, techniques, principles, laws, concepts, percepts, and factual data needed for the implementation of the present concept of design.

The first of these two types of graduate programs should emphasize:

- the extension of the design process into the planning period of the system life cycle;
- the extension of technological factors and quantitative techniques into system management; and
- the development of decision and utility theory and its application to the design process (value modeling, evaluation, and decision).

The need for and the significance of systems engineering education in general and graduate education and research in particular is so apparent that there are active efforts in this respect even outside academia. One of the most characteristic examples is the contribution to system education by the National Astronautics and Space Agency (NASA). NASA had two programs of training in this area: one for faculty, the other for predoctoral students. The following description of these two programs is adopted from [19]. The Summer Faculty Fellowship Program was started in 1966 in cooperation with the American Society for Engineering Education. The objectives of this program were:

1. To increase competence and to develop concepts which will enable participants to organize multidisciplinary engineering systems design programs and courses at their home institutions.
2. To establish and further communications and collaboration between engineering and other disciplines.

A university and a NASA center joined in running an 11 week program where the faculty fellows participated as members of multidisciplinary design teams in the design of a complex space system. In the summer of 1969 there were four programs: Stanford University in cooperation with the Ames Research Center, University of Houston/Rice University with the Manned Spacecraft Center, Old Dominion University cooperating with Langley Research Center, and Auburn University/Univeristy of Alabama with the Marshall Space Flight Center. A total of 80 faculty members were enrolled, which made a grand total of 245 since program inception.

The student program was a bolder step and led to a doctoral degree in engineering based on team participation by students and faculty in realistic engineering systems design problems. This was a pilot program at five universities: Cornell, Georgia Institute of Technology, Kansas, Purdue, and Stanford.

NASA and its industrial contractors indeed provide a reservoir from which relevant and challenging systems design problems can be drawn. Further, NASA makes available its facilities and staff as may be needed for faculty and students to develop and pursue systems design studies. In the federal agencies, only the military and aerospace sector have been doing systems design to any great extent and therefore have the expertise to contribute.

Through fiscal year 1969, NASA has funded a total of 73 three-year traineeships at the five schools.

It is clear from the foregoing review that a great deal of searching has taken place and is taking place in this field. And it is also true that in many instances systems engineering curricula have not been planned and engineered as an entity, but rather on a fragmented basis, and include various conglomerations and mixes of

engineering and math courses, electrical circuitry theory, control theory, communication theory, etc., and tools and techniques courses, which are not necessarily equivalent. The search for a common ground or basis in all these endeavors is the main goal of this study.

3.2 Methodological Considerations

The question regarding the scope and content of systems science and engineering education might be answered more readily if it is preceded by the analysis of methodological approaches which have been considered in this subject area. Essential to, or even in a sense equivalent with the concept and content of the methodology of systems science and engineering are the concepts of "systems approach" and "total systems design", both of which are extensively used in professional literature.

According to Howard, the methodology of systems engineering should, first of all, provide for a systematic identification of total system requirements, on an overall basis. It provides a means for developing hardware, facilities, personnel, logistics, and procedural support information on a concurrent and integrated basis--specifically to minimize oversights in design, optimize the design and reduce costs. Implementation of the methodology for large complex systems requires a major effort utilizing top design engineers [22].

He makes the following point:

> "...successful planning and design of complex systems requires the systems approach. The systems approach recognizes the interrelationships which tie a system together; it recognizes that the interactions among subsystems and elements cannot be ignored; and requires that the parameters of the system be extended outward as far as is reuqired to determine which interactions are significant to the design problem.
>
> In its application--the systems approach requires that the system be planned and designed as an entity to satisfy the needs of the user. The implementation of the systems approach requires the application of a rational methodology of systems engineering.
>
> No two systems are ever alike in their developmental requirements. There is, however, a common and identifiable methodology and process for arriving at logical system decisions regardless of system purpose, size, or complexity. The methodology and process are delineated in the paper and the framework for doing systems engineering is established. Systems engineering is basically organized design engineering.
>
> Formalizing systems provides systems development groups with the technical know-how for designing the most effective systems under specified constraints. It provides a recognized framework for a unified total engineering effort and for communicating the required itnegrated and documented technical information and system visibility vital for (1) decision-making, and (2) planning and control of the engineering and resources. Only within the framework of formalized systems

engineering can we achieve the required organization, planning, scheduling and control of the total system development effort of highly complex systems." [22]

It is important to note that "systems approach" or "total systems design" or, in other words, the methodology of systems engineering, is also relevant to non-engineering systems. As an illustration we quote from a report prepared by Physiology Training Committee, National Institute of General Medical Sciences, National Institute of Health [34]:

> Physiologists have in common a point of view--that of the systems approach. A scientist is a physiologist when he concerns himself with the dynamic properties of component arrangements. The modern concern about these dynamic properties goes beyond the historical interest and function though the two are of course related. They differ in that the historical concern was mainly for the observation of function and its qualitative description. Quantitative description sometimes followed, but, if so, the emphasis was strongest upon steady-state quantification. In modern Systems Physiology, the emphasis is upon the dynamic properties of system arrangements as revealed by their transient responses, and with this changed emphasis comes a more explicit strategy of research--one common to other branches of natural science.
>
> Admittedly a strategy of research, particularized, turns upon the personality and the inclinations of the scientist conducting the investigation, yet modern physiology has such a strong conceptual basis in systems theory that an illustration of a generalized strategy can be given. Of course, other approaches are possible and effective, but the one given here typifies the activities of the Systems Physiologist.
>
> General steps in Systems Physiology, common to other branches of natural science, include the following (but not all steps are necessary or possible in every case):
>
> - Choice of a system of interest;
> - Choice of the describing variables to be measured;
> - Selection of measurement techniques and estimate of errors of measurement;
> - Estimate of the relevant time domain for system activity and transient responses. Does the system respond over milliseconds, seconds, minutes, days, months, etc.?
> - Choice of sampling rates appropriate to the time domain (when discontinuous measurements must be made);
> - Choice of stimuli, input signals or forcing functions to perturb the system.
>
> These obvious steps comprise the stage of planning. The following five steps comprise the stage of experiment:
>
> - Observation of the performance of the system without experimental perturbation (non-interacting experiments);
> - Observation of transient and steady-state responses of the system following perturbation;

- Proof of recoverability (Can the system recover its initial state after perturbation, or is it permanently altered?);
- Experimental intervention to discover components and connections within the system, and coupling between it and other systems:
- Mapping of signal flow pathways and components into an operational diagram showing the connectivity of the system;
- Determination of the dynamics of isolated components.

At this point in the stage of experiment, it becomes necessary to identify the "unit processes" that underlie the component process dynamics. (This analytical step is essential for the subsequent synthetic stages of systems physiological work).

Systems Physiology then proceeds to the stage of modeling:

- Development of a model that incorporates the unit processes of components, to stimulate selected system performance characteristics.
- Test of the model (almost always, except in elementary cases, a computer is necessary). The model must be tested for adequacy in reproducing the data that served as the basis for the model--this is the minimal criterion for a satisfactory model. A more powerful model will serve to make predictions of system performance under circumstances not directly incorporated into the development of the model.
- Experimental tests of predictions by performance of the analogous experiments on the real system.
- Modification of the model; further predictions and modifications within the same general structure.
- Development of a new kind of structure for the model and fresh kinds of predictions and experiments.

Without pursuing the topic of methodology in too great detail, one can observe the significant fact that, contrary to the subject matter coverage of systems science and engineering, there is much more agreement and considerable less variance of the opinion how the problems falling into systems area should be approached. This is an important observation for the further dicsussion of the educational programs.

3.3 Design Orientation of General Engineering Curricula

Before analyzing various aspects of systems science and engineering curricula as academic disciplines, it is pertinent to ask the question how much of the essence of these programs is contained implicitly in general engineering curricula and, in particular, how much design oriented are general engineering curricula. No comprehensive studies of this nature have been reported for a representative cross-section of universities and colleges, but some inferences regarding the state of affairs can be made from the very thorough analysis of the engineering curriculum of the Univerisy of California in Los Angeles by Lifson and Kline [27]. Having examined the undergraduate four-year engineering curriculum and the complete listing of some 264 undergraduate-graduate course offerings in the 1966-1967 Announcement of the UCLA College of Engineering, they summerized their findings and comments as follows:

> "... A major portion of the engineering courses (46%) were concentrated heavily in the area of analysis, a lesser, but significant, emphasis was given the areas of synthesis, evaluation, and optimization, and very little treatment was given the other activities of the design process. This emphasis on analysis, and the relative neglect of value modeling and decision making are believed to be typical of engineering curricula.
>
> Evaluation and decision were taught and practiced, but only in a somewhat primitive fashion, largely based on deterministic and go/no-go binary decision criteria. Until recently, optimization was carried out, primarily by the use of unconstrained functions (ordinary calculus) or by the use of various "programming" techniques. Design iterations were made to obtain further design improvements largely without regard to the worth of the next increment to be gained by going around the loop once more, i.e., without explicit cost-benefit considerations.
>
> The formulation of a value model - including an objective criterion of the worth of the system being developed - was neglected in the engineering curriculum. Until recently, value modeling was not generally considered an engineering function, perhaps because the engineer may be uncomfortable when dealing with personal values, subjective probabilities, and uncertain environments - the basic elements of evaluation and decision.
>
> With respect to the system life cycle, a large percentage of the courses were fairly uniformly distributed in the preliminary design, development, and detail design stages. Smaller percentages of the courses dealt with system definition and concept formulation. Production design, production,

installation, and use were only touched on in a few courses. The management of engineering was almost entirely neglected."

The results of the analysis of the undergraduate and graduate courses offered by the college of Engineering of the University of California in Los Angeles in terms of their relevance to specific phases of the systems engineering process are shown in Table 3 and Table 4. Although no systematic comparisons were made, it is felt that this state of affairs is indicative of general engineering curricula in most other universities.

Table 3. UCLA College of Engineering: Number of Lower Division-Upper Division-Graduate Courses Relevant to Specific Phases of the Engineering Process

System Life Cycle				GATHER AVAILABLE INFORMATION	FORMULATE VALUE MODEL	SYNTHESIZE ALTERNATIVE SOLUTIONS	ANALYZE AND/OR TEST	EVALUATE	DECIDE	OPTIMIZE	COMMUNICATE
				3-32-2	20-74-21	4-132-74	47-273-276	4-67-64	3-35-14	3-41-65	3-32-0
		MANAGEMENT	0- 5- 6	0- 0- 0	0- 0- 1	0- 1- 1	0- 1- 1	0- 1- 1	0- 1- 1	0- 1- 1	0- 1- 0
PLANNING		CONCEPT FORMULATION	14- 65- 23	1- 6- 1	7-15- 4	1- 9- 5	1- 9- 4	1- 9- 4	1- 5- 3	1- 5- 2	1- 7- 0
PLANNING		SYSTEM DEFINITION	14- 88- 70	1- 6- 1	7-18- 4	1-19-17	1-17- 24	1-12-15	1- 5- 3-	1- 5- 14	1- 6-0
PLANNING	ENGINEERING	PRELIMINARY DESIGN	11-137- 99	1- 6- 0	5-18- 5	1-34-21	4-45-29	1-15-20	1- 6- 4	1- 8-20	1- 5- 0
ACQUISITION	ENGINEERING	ENGINEERING DEVELOPMENT	19-174-181	0- 5- 0	0- 9- 5	0-31-21	19-96-116	0-13-17	0- 6- 3	0- 9- 19	0- 5- 0
ACQUISITION	ENGINEERING	DETAIL DESIGN	23-164-139	0- 5- 0	1- 8- 2	1-30- 9	19-93-132	1-11- 7	0- 8- 0	0- 9- 9	0- 5- 0
ACQUISITION	ENGINEERING	PRODUCTION DESIGN	3-38- 0	0- 3- 0	0- 5- 0	0- 7- 0	3- 8- 0	0- 5- 0	0- 4- 0	0- 3- 0	0- 3- 0
ACQUISITION		PRODUCTION AND INSTALLATION	0- 6- 0 0- 0- 0	0- 1- 0 0- 0- 0	0- 1- 0 0- 0- 0	0- 1- 0 0- 0- 0	0- 2- 0 0- 0- 0	0- 1- 0 0- 0- 0	0- 0- 0 0- 0- 0	0- 0- 0 0- 0- 0	0- 0- 0 0- 0- 0
USE			0- 4- 0	0- 0- 0	0- 0- 0	0- 0- 0	0- 2- 0	0- 0- 0	0- 0- 0	0- 2- 0	0- 0- 0

Table 4. UCLA College of Engineering: Percentage of Course Offerings Relevant to Specific Phases of the Engineering Process

					GATHER AVAILABLE INFORMATION	FORMULATE VALUE MODEL	SYNTHESIZE ALTERNATIVE SOLUTIONS	ANALYZE AND/OR TEST	EVALUATE	DECIDE	OPTIMIZE	COMMUNICATE
					3	9	16	46	10	4	8	3
			MANAGEMENT	0.9								
SYSTEM LIFE CYCLE	PLANNING	ENGINEERING	CONCEPT FORMULATION	8	3	10	5	5	5	3	3	3
SYSTEM LIFE CYCLE	PLANNING	ENGINEERING	SYSTEM DEFINITION	14	3	10	14	16	11	3	8	3
SYSTEM LIFE CYCLE	ACQUISITION	ENGINEERING	PRELIMINARY DESIGN	19	3	10	21	30	14	4	11	2
SYSTEM LIFE CYCLE	ACQUISITION	ENGINEERING	ENGINEERING DEVELOPMENT	29	2	5	20	87	11	3	11	2
SYSTEM LIFE CYCLE	ACQUISITION	ENGINEERING	DETAIL DESIGN	25	2	4	15	87	7	3	7	2
SYSTEM LIFE CYCLE	ACQUISITION	ENGINEERING	PRODUCTION DESIGN	3	1	2	3	4	2	2	1	1
SYSTEM LIFE CYCLE	ACQUISITION	PRODUCTION AND INSTALLATION		0.5								
SYSTEM LIFE CYCLE	USE			0.3								

3.4 Design Stems of Engineering Curricula

To some educators, systems engineering is more or less equivalent to that portion of an engineering curriculum which deals with design. To others, this viewpoint appears to be too limited since most of the engineering is designing. To the latter, the complexity level of the system to be designed is the essential criterion which is to be applied in determining whether or not the problem is a systems engineering problem. Most, however, would agree that courses emphasizing design aspects are indispensible in any systems engineering program. In this spirit, the role of the systems engineering is to emphasize that if an engineer's primary function is condisered to be gathering, organizing, and processing information so that rational decisions can be made at each stage of product or process design and implementation, that of a systems engineer is even more so.

In the sense that systems engineering can be considered a discipline focused on design, courses which purport to emphasize design methodology and which are intended to give students an opportunity of design experience are of direct interest in this context, whether an institute offering such a course has a formal systems engineering program or not.

To begin with, we shall quote the description and objectives of a design course which has been prepared by the Systems Engineering Program Group, Department of Operations Research and Systems Analysis, Polytechnic Institute of Brooklyn.

Catalog Description:

450-1 <u>System Design and Societal Problems I, II</u> 2:3:3 each

A one year sequence utilizing team efforts towards realizing large scale societal system design feasibility proposals. The approach will be to emphasize student involvement, self-study, student teaching, guest speakers, and seminar discussion. Outside investigations and consultative contacts will be employed. Typical study areas include health care, transportation, environmental control, urban dynamics, bioengineering and general societal problems. Multi-disciplinary teams will study specific problems during the year with their work culminating in final written and oral reports.

Prerequisite: At least junior standing. Approval of both departmental advisor and course director.

The implementation of this course envisions that the class divides itself into two to five groups, each made up of 6 to 15 students. Student groups may propose their own projects for approval. Alternatively, each group chooses a project for the year from a list made available by the staff administering the course.

Each group has assigned to it a faculty "preceptor" who acts as the prime consultant to the students and remains in close contact with his student members throughout the year. In addition, a course director coordinates the conduct of the course.

The two 1 hour sessions are mainly used by the students as consultation periods with their faculty preceptor. While faculty lecturing is minimized these 1 hour sessions may also be used for student lecture presentations, seminars, and guest speakers as student motivated and as appropriate. The three hour sessions are used for student oral presentations, laboratory work, field studies, computer simulation work and library investigation. Each student receives one grade at the end of the year, assigned by his preceptor, which replaces the S or U grade assigned at the end of the first semester.

The teams themselves define sub-problem areas which they divide amongst themselves for study in smaller groups. Typical problem areas are listed below:

- Mobile Maternity Hospitals
- Automobile Ban
- Protein Deficiency
- Underground Utilities
- Multiphasic Health Screening
- Design of an Overall Air Traffic and Ground Transportation Link System for Long Island
- The Problem of Waste Reduction and Recycling and Their Effect Upon Industry and Life Style
- Underwater Resources
- Education Reform
- Postal Reform

It is intended that this course be taken as a junior technical elective, although seniors may also participate. From a study of the catalog it appears that all departments can accommodate this proposed junior course by replacing electives currently in the curricula and some minor shifting of courses from the junior to the senior year.

Another example of a characteristic approach to and administration of systems design courses are the projects courses at Stanford University. We quote below extensively from an article by Lusignan and Hafferty, in which these courses are described [28]:

A significant experiment in urban engineering is taking place during the 1969-70 academic year at Stanford University. A two-quarter graduate-level course, Housing and Urban Resource Development, has been introduced within the School of Engineering curriculum. The principal focus for this project-oriented course is the City of San Francisco, with the class objective being to identify as completely as necessary the way the city

should be developing by 1990. This 20-year development strategy will be supported by detailed specification and design of system, institutions, and community structures required in the next decade to guarantee progress toward the longer-term goals. Particular emphasis will be placed on the provision of healthful life styles for San Francisco residents, with adequate housing opportunities being given first priority.

In the true spirit of urban engineering, the Stanford course is a fully interdisciplinary effort, involving some 150 students from 22 major departments and 15 faculty advisers from such disciplines as architecture, business, law, anthropology, philosophy, medicine, engineering-economic systems and electrical, industrial and mechanical engineering. For the duration of the study, the group will be divided into 12 project teams, each developing a complete strategy for a particular aspect of the urban fabric."

These project teams dealt with the topics of physical community design, housing production, transportation, community services, cultural development, city changes, implementation strategy, labor and building codes, public financing, and financing of hoursing. Contributions of each team were integrated into a coherent overall project strategy through formal interface groups and informal communication.

"Management of the project is performed entirely by students, with each task group delegating a leader to serve on the project management staff. This body in turn selects a project manager who, with the team coordinators, has the responsibility for establishing general class goals and for organizing and directing the progress of the teams toward their goals. Beginning with a two-week "wild ideas" session intended to stimulate innovative thinking, the project is progressing through three major phases in which alternative strategies are identified, data are gathered, comparative analyses are performed, and final decisions are made.

Important orientation to San Francisco's unique problems and timely background information on urban affairs in general are being provided by a series of guest speakers, representing such agencies as Housing and Urban Development (HUD), Health, Education and Welfare (HEW), and the National Association for the Advancement of Colored People (NAACP) in Washington and the planning department, redevelopment agency, and the mayor's office in San Francisco. In addition, the class is addressed by spokesmen for local citizens groups, academicians, and private professionals active in urban affairs. Class members spend many days working in the city collecting additional data and involving residents in the study.

Stanford's interdisciplinary experiment in urban engineering is an outgrowth of previous experience with systems engineering courses. The project-oriented approach, class organization, and administration presently being employed were developed over the past seven years in such project courses as Satellite Systems

Design and, more recently, Ocean Engineering. Though having a major technical component, the earlier courses also had major social, economic, and political components as well. For example, one of the satellite courses concerned the use of high-power satellites to bring educational television to Brazil, India, and Indonesia; and in the study major direction came from the education and economics students, not the engineers.

> The principal academic aim of Stanford's urban engineering course, as with earlier systems engineering efforts, is to enable the student to understand other areas involved in broad systems problems and to teach him to work competently with other members of an interdisciplinary team. A related objective, particularly relevant in urban studies, is to overcome limitations in the student's education in his own major. Most courses enable him to understand and choose the appropriate relationship or theory to answer a specific question, but they give him little guidance in sorting through the maze of a complicated socio-technical problem--deciding what questions are most important to ask, what are the critical parameters, and how approximate one can be in estimating the answer. This ability is best obtained in a project course, and interdisciplinary systems studies make very efficient project courses.
>
> A third benefit which students derive form the experience is an intensive and timely view of the world in which they plan to pursue their careers. The problems, existing groups seeking to solve the provlems, and the methods currently being used are brought out. This exposure has in the past significantly affected students' professional interests and choices.
>
> And finally, a major benefit of the systems course accrues directly to society. Topics chosen for study concern real problems, and the students' findings, supported by the experience of the faculty and guest speakers, have made tangible contributions to the solution of these problems. For example, the satellite TV proposal did result in the Brazilian government's undertaking such a national project."

An enthusiastic promoter of systems design projects, Prof. W. Bollay, who believes that such project courses should become an essential component of any engineering curriculum, has the following to say on their organization and structure [6]:

> "These university-based systems engineering projects are generally open to second-semester seniors and graduate students. The class is organized into groups of 10 to 15 students, and each group elects its own student group leader. The class also elects its own student project manager. The term of office in these elected positions is about a month, so that a reasonable percentage of the students also get some experience in project management. The project duration is four to five

months and requires about one-fourth of the student's time. The students include participants form all of the disciplines which have a bearing on the problem. Thus, typically a class includes students from various fields of engineering, as well as 10-20% from the School of Business Administation. Also it includes students from the pertinent physical and social sciences, as well as other professional schools such as law, education, etc. Each student group has a sprinkling of disciplines. In this manner, students from different fields interact directly with each other and participate in solving the interaction problems and make compromises between what the planners might ideally like, what the technologists can develop, and what appears economically feasible.

One faculty member serves as the organizer and director of the course. He selects the project topic for the year, and he makes arrangements for a group of lecturers to present to the class the background in the problem area and the present state of the art in the technologies pertinent to the problem. In addition, there is one faculty adviser for each student group. Lectures on the fundamentals of various subjects are presented by the university staff. Most of the other lecturers are from industry or government and are carefully selected so as to bring to the class the best possible understanding of the current situation."

As to the selection of the topic for such a project, Prof. Bollay recommends that it should always represent a real situation of current interest to both faculty and students. Furthermore, it should preferably be one for which there exists some expertise on the campus and in which a number of departments have a great research interest.

Finally the subject matter of the systems project should ordinarily be a system which does not yet exist and which has not been previously studied in depth by industry or government. The ideal system is one which is just beginning to become feasible with the current state of the art and which will have a reasonable chance of being developed during the coming one or two decades. Such projects, says Prof. Bollay, capture interest and imagination of the students, since they may have an opportunity to participate in the evolution of these future systems during their early professional careers.

How one goes about solving a selected problem has a direct bearing on the motivation of students for the project. We quote:

"One of the important objectives of the course in systems engineering is to give the students an opportunity to parti-

cipate in both the formulation of the problem as well as in the solution by a preliminary design. "A problem well put is a problem half-solved" is as true for a systems engineering project as for a research investigation. Thus, ordinarily the project starts with a question about a problem area and a "hunch" about a possible solution. The precise definition of the design objective and the proposed solution are usually arrived at by a series of iterations... (For example, in the case of an educational satellite system), the educators may specify what they might ideally like as an educational program for the village schools in Brazil, the electrical and mechanical engineers prepare parametric studies showing the technologically feasible alternatives for a satellite communication system, and the business students and economists prepare cost estimates and analyze the possibilities of financing such a satellite system. The final definition of the problem is usually quite different form from the initial rough conception of the system. For example, it was found desirable to have the educational satellite system serve a multiple function--two-thirds of its capacity during the day for instructional television relay to the schools and one-third for the relay of telephone and teletype communications. During the evening hours, the instructional television channels were used for adult education and entertainment; during the night hours, the entire system was used for relay of teletype and other electronic communications. Such a system could be financed on the basis of loans from international banks.

The essence of the systems approach to problems consists in taking this broader look, both with respect to real objectives and possible solutions. In a system study of a problem, the various alternative solutions are analyzed, as well as their advantages, disadvantages, and implications. For example, a surface microwave system or the mail system could be used for relaying educational television programs to all of the schools of a country. A simple analysis showed, however, that mailing films or videotapes to all of the schools of a country would be far too expensive. A comparison of communication satellites with surface microwave systems showed that each had advantages and disadvantages. It was concluded that future communication satellites would have a considerably lower amortized annual cost than surface microwave systems.

Each, however, has its own potential disadvantages. The communication satellites would have to be replaced periodically, perhaps every 5 to 10 years, and thus either a spare satellite must be capable of being launched rapidly or a spare must be available in orbit and be capable of being moved into the desired position at very short notice. The surface microwave systems have the disadvantage of being susceptible to easy sabotage. One great advantage of communication satellites which was noted by a Brazilian planner is that they overcome one of the greatest obstacles which previously impeded the development of the interior of Brazil--they provide both ready communication and the possibility of obtaining a first-class education even if a family lives away from the large cities.

This implication for communication satellites may well be the deciding factor in their final acceptance in Brazil."

In conclusion, the following comments are made on the implementation, cost and success of project design courses:

"The student projects at M.I.T. and Stanford have demonstrated that second-semester seniors and graduate students have reached a level of technical competence where they can perform very well on such interdisciplinary systems projects. Their performance with respect to ingenuity and inventiveness is as high as, or higher than, that of most industry teams. The student teams do not have much experience and thus usually require more time, because they go down more unproductive dead alleys. On the other hand, they are ordinarily more enthusiastic and hard-working and probably produce more original concepts than the typical industrial design team. Teams of young professors perform about equally as well as the student teams. The older professors do not usually adapt as well to the interdisciplinary projects unless they have had industrial systems experience. Their greatest contribution in systems engineering projects is normally as consultants in their own field of specialization.

The direct cost of organizing and managing a major systems engineering project at a university, including the cost of staff, visiting lecturers, and publication of a final report for a class of 50 to 60 students is on the order of $20,000 to $25,000. This is about one-fifth of what this same project would cost if it were carried out in industry or by paid university staff.

From the standpoint of educational benefit, as well as the output of new concepts and ideas, there is little question that the systems engineering projects at M.I.T. and Stanford have been highly successful. The factor which has impeded the development at many other universities has been the higher cost of such project courses compared to standard lecture courses. It would, however, be very cost effective for the federal or state gevernments to support systems engineering projects concerned with problem areas of interest to them."

As a final example of the ongoing efforts to emphasize the design aspect of complex systems as part of system engineering curricula, we give a description of a design project organization from a report on the Systems Engineering Design Summer Faculty Fellowship Programs conducted at the Marshall Space Flight Center (MSFC) by Auburn University and the University of Alabama, one of the four programs sponsored by the National Aeronautics and Space Administration and the American Society for Engineering Education [45]:

"The eleven-week program has three basic phases:

1. The first phase consists of generating background information on the study area and preparing a preliminay report on what the participants believe they will accomplish, how they should divide themselves to work on the project, and what will be required in the way of information to complete the training exercise.

2. The second phase involves developing alternate approaches to the requirements for the general objective established in the first phase, redefining the objective to some extent and evaluating the alternatives.

3. The last phase involves trade-offs of the alternatives and selection of the final approach to satisfy the general objective.

Each phase lasts about three weeks, preceded by a week of orientation activities and concluded by a week of presentation of results.

First week. On the first day, the participants were processed into the center and during the afternoon an introductory lecture on the systems approach was presented. On the second day, a tour of MSFC took place in the morning and in the afternoon a series of orientation lectures were given on the activities of the MSFC space-station/space-base concept. On the third day, the participants were informed of the program organization in more detail.

Participants elect a project leader and group leaders three times during the program, but these leaders were not elected until Friday afternoon of the first week. Thursday and Friday were filled with additional technical lectures. During the last two days of the first week, each participant introduced himself, discussed his technical interests, and described his background. The project leader was elected by the participants rather than selected by the staff, the election taking place after a few days of association. By electing their project leader, the participants must accept him and assist him in accomplishing their tasks.

Second week. Orientation lectures related to the study project continued through Monday and Tuesday. The remainder of the week was spent in a tour of the NASA facilities: the Michoud Assembly Facility in Louisiana, the Manned Spacecraft Center in Texas, and Kennedy Space Center in Florida. This tour provided the overall integration of the operation of the Office of Manned Space Flight, along with an overview of the complexity of the objective of a man-on-the-moon. The enormous task undertaken by NASA gives the participants an understanding of how the systems approach is used in solving complex multidisciplinary problems.

Third week. The third week was devoted to additional seminars and presentations. The participants were aware that on the third day of the fourth week their first interim

report would be due. Individual participants were escorted to various MSFC contacts in order that data generation could be initiated. At the same time (through informal get-together and seminars), the participants were always reminded of the program objective. It was explained that they were in the translation phase of their systems approach where they were actually trying to relate the objective, the criteria, and the constraints. A monetary constraint was not established at this time.

Fourth week. The fourth week brought the first tangible quantity. The first interim report was rather substantial (50 typewritten pages), but it resembled a collection of short stories rather than any integrated effort to define requirements and alternative approaches, althoufh this was what had been requested. Background information had been gathered during the first phase, and some initial attempts had been made on the project. Subsequent to receiving the first interim report, a seminar was held on Thursday of the fourth week to emphasize that requirements and alternative approaches would have to be defined during the next phase. The staff was confronted by the participants, who felt they had not been given enough detailed direction to achieve the finished project. In this instance, it was necessary for the staff to exercise tact, since the staff members were not functioning as project directors. Part of the systems approach training is to have the participants develop these criteria, procedures, and detailed approaches on their own.

Fifth and sixth weeks. During the fifth week the second set of project and group leaders were elected. The staff continued to provide seminars on a reduced schedule and let the participants request information which they thought was necessary. At this time and into the sixth week, numerous meetings were held by the leaders and their groups. Each week the staff scheduled one large meeting of all participants, at which time they could communicate with each other. There was quite a bit of resentment and resistance to these meetings as the participants believed such meetings were a waste of time. However, they provided a valuable communication link and were useful. Although everyone thought that the communications were excellent, small items would emerge: e.g., one task group was planning on the use of water generated from the fuel cells on board the embryonic space station; the other task group in charge of power systems had no plans to use fuel cells.

Seventh week. The second interim report was due on Wednesday of the seventh week. It was considerably longer and better organized than the first interim report. The report was carefully critiqued by the staff, the critique consisting of asking questions which would indicate items that had been omitted or considered in a rather "cavalier" fashion. The third election of project and group leaders was held on Friday of the seventh week.

Eighth week. On Monday of the eighth week, the participants were informed that they would have to give a presentation to one of the MSFC executives. They worked seriously preparing viewgraphs and other material. On Friday, they gave their presentation which lasted most of the morning and were asked some pointed questions by MSFC personnel connected with space-station/space-base projects. They withstood the questions well, but new questions arose. In fact, many of their alternatives were shown to need more development in unison. What they had done was try to effect a trade-off prematurely with inadequate information. Since at this stage the participants were unaware of this premature judgment, they still were to benefit from the training objectives of the program.

Ninth and tenth weeks. During the ninth week the participants were to effect trade-offs, which took all of the ninth week and the first day of the tenth week. In the tenth week they were to work on the final draft of their report, which was due on Friday, and prepare for the final oral presentation, which was the third day of the eleventh and last week.

Eleventh week. Dry-runs of the final presentation were made on Monday and Tuesday of the last week and these were preceded by some informal dry-runs by the participants. The participants decided on how they would give their final presentation, and they tried to provide everyone a speaking part which was recorded on videotape during the actual performance. The participants selected a panel-type presentation, with a moderator preceding each panel. In about the eighth week the participants had decided to give a final presentation. In preparation for the final oral presentation, Communications Skills, Inc., was engaged for several sessions to assist the participants in preparing their verbal presentation. A closed-circuit television camera was used, and the participants were critiqued individually on an informal basis by the instructor. The participants felt this CCTV was beneficial to their presentation and personal ability to communicate."

In summary, there seems to be a broad agreement on the need for design-oriented approach in new engineering curricula developments in general and in systems engineering in particular. It is also of essence that all the activities of the design process, together with the supporting tools and techniques needed for quantitative representation and study, should be included in the curriculum. Specifically design should be introduced into the curriculum through (a) explanation and demonstration of the systems methodology (b) projects requiring the application of the design process at all levels of the system, and (c) design enrichment of all stems of the engineering curriculum through applications of mathematics and science to design decision making. This in turn would entail the extension of technological factors and

quantitative techniques into system management and the development of decision and utility theory and its application to the design process (value modeling, evaluation, and decision) [27].

With respect to the program level, it is maintained by some that

"the rational, quantitative implementation of the design process in planning, engineering, and management presents a challenge primarily suitable for Masters and Ph.D. programs. Such programs include research into new approaches to value modeling, synthesis, analysis, evaluation and optimization, and decision making, as well as the application of developed techniques to the planning and design of complex systems. In particular, automation of the design process and the optimal mix of men and machines in decision making need investigation.

The doctoral and masters program in design would be supported by courses with titles such as:

Applications of Decision and Value Theory in Design
Synthesis of Large-Scale Systems
Dynamic Elements of Operational Systems
Techniques of System Optimization
System Simulation
Statistical Design of Engineering Experiments
Selected Topics in Engineering Statistics
Stochastic Processes in Linear Systems
Economic Evaluation of Engineered Systems
Economics of the Engineering Function
Computer Aided Design
Engineering Management
Engineering Economics of Development
Engineering Resource Economics

Such courses would form the basis for research leading to the doctorate. Two types of graduate programs should be incouraged:

1. An application of the systems engineering methodology to the solution of a significant design problem.
2. Research in depth into the activities, tools, techniques, principles, laws, concepts, percepts, and factual data needed for the implementation of the present concept of design [27].

Lifson and Kline recommend that in order to prepare students for graduate studies of the above type, the undergraduate design stem should include the following:

• Instruction in the methodology and application of the design process in the lower di ision, preferably at the freshman level. As soon as possible, the engineering student should be made aware of his role, of the differences between the engineer and the scientist, and of the contributions which the other stems of the curriculum are making to his capabilities as an engineer. Instruction in the methodology and

its application in significant design projects should continue through the senior year. Increasing sophistication and depth in design projects can be required as the student progresses through the mathematics and science stems and acquires capabilities in his technical specialty. These design experiences must encourage creativity and provide for experimentation.

- Probability and Statistics. Since the engineer inherently deals with uncertainty, this branch of mathematics is essential to his applying the design process.
- Computer Applications and Programming. The digital computer is essential for the synthesis, analysis, evaluation, optimization of complex systems.
- Decision and Utility Theory. Value modeling, evaluation, and decision are essential acitvities of the design process. Elementary decision and utility theory provides a theoretically sound basis for introducing these activities to undergraduates.
- Economics and Engineering Economy. Design inherently involves the allocation and consumption of resources and the evaluation of the effects of implementing alternative candidate systems. Economic worthwhileness and financial feasibility are fundamental to design decisions. Economics and engineering economy should be included in the design stem if they are not provided elsewhere in the engineering curriculum [27].

3.5 Interdisciplinary and Intradisciplinary Aspects of Systems Engineering

It is customary to associate systems engineering with engineering related to interdisciplinary problems. And in many instances it is, although there is no obvious reason to limit systems engineering to such problems alone. We shall discuss this aspect first, especially since the word "interdisciplinary" is interpreted differently by different people.

To some people interdisciplinary does not mean a new discipline that somehow combines various parts of the older disciplines; rather it means a team concept, establishing the mechanisms whereby individuals in different disciplines can work together to solve problems that require inputs from many areas.

For example, to solve urban problems, professions do not have to be abolished in favor of a new "urban engineering" profession; rather, each profession should be improved by developing the ability to communicate with other professions. Thus, planners, architects, economists, sociologists, doctors, lawyers, politicians, civil, mechanical, electrical, industrial engineers, etc., must develop the capacity to work together. And the cities must develop means to use these professionals as teams, continuously working together--not just meeting together over lunch once a week or on an advisory panel for a few days [28]. Under such circumstances we may say that systems engineers use interdisciplinary approach.

To others "interdisciplinary" does mean a discipline or a meta-science encompassing certain branches of knowledge traditionally considered as separate disciplines. In this interpretation, systems science has strong relation to the philosophy of science and in some sense could be viewed as a new "philosophy of engineering".

Whatever might be the particular interpretation of the concept of "interdisciplinarity", it was found significant enough to be listed among the goals of engineering education in the report by the Committee which worked on this study with National Science Foundation support. Among the seven major suggestions of the Committee, one reads:

> "There should be expanded opportunities for inter-disciplinary study."

Again, if we analyze the motives which led to this emphasis on "interdisciplinarity", we cannot fail to note that the complexity of problems which face today's engineers led to the transition from "subject specialist" to "problem specialist" who should know all those things from various disciplines which are necessary to analyze and solve the problem. This however is possible only to certain limited extent. Hence the tendency to set up teams of specialists in order to pool the talent, say, of physiologists, neurologists, biophysicists, biochemists, biologists, mathematicians and what not in order to work on the solution of some particular problem. This is the reason why systems engineering does imply to some people a team approach to problem solving. Nevertheless, there is no inherent reason to consider team approach as an essential characteristic of the discipline although consideration must be given to it when applying systems engineering methodology in practice.

Nor is it in our opinion essential to associate systems engineering just with interdisciplinary problems. The systems approach is equally applicable to problems within single discipline since it is not the multi-disciplinarity, but the degree of complexity which determines the type of capabilities expected from the problem solver. Examples of complex problems requiring systems approach abund in power systems engineering, computer design, chemical engineering, etc.

Along these lines it is instructive to note that, for example, biologists now favor a classification of their activities according to the levels of organization at which they work, i.e. to approach the problems from the systems point of view, at different levels of resolution, rather than according to their specialties. Thus we have molecular biologists, cell biologists, organ system and organism biologists, and population biologists. Men working at each level of organizaiton find communication with others working at the same level quite natural, regardless of what variety of life--plant, animal or bacterial--may be the particular object of study at a given level. In contrast, communication between men working at different levels of organization is not so easily achieved, and may fail so conspicuously as to lead to misunderstanding, suspicion, condescension, or even hostility and a cold lack of interest [34].

3.6 Interaction with Other Disciplines

A predominant note in the preceding deliberations on the nature of systems engineering was the interaction with other disciplines. The interaction is particularly close with disciplines such as industrial engineering, operations research and others which are inherently concerned with complex systems, systems analysis, and systems design problems. The partial overlap of interests of systems engineering on one hand and "systems oriented" disciplines of various kinds on the other hand is clearly reflected in the descriptions of the latter which appear in college catalogues and other related publications.

For instance, the official definition of industrial engineering given by the American Institute of Industrial Engineering is as follows:

> Industrial Engineering is concerned with the design, improvement, and installation of integrated systems of men, materials, and equipment. It draws upon specialized knowledge and skill in the mathematical, physical and social sciences together with the principles and methods of engineering analysis and design, to specify, predict and evaluate the results to be obtained from such systems.

The boundaries between systems engineering and operations research are particularly fuzzy. The Stanford University catalogue states that the operations research program is concerned with:

> A. The study of the abstract mathematical structure of models derived from real life situations such as allocation models of an enterprise or an economy, network and flow models of transportation and communication systems, reliability models of complex engineering systems, queuing models of congestion, control models of systems overtime, discrete selection models for routing and pattern cutting, policy decisions for production and inventory control, and models for conflict resolution;
>
> B. The development of the mathematical theory necessary for the solution of these models, and with the theory of optimization when some measure of relative desirability of alternative solutions is available

Most of the tasks mentioned above could definitely be considered as being in the area of interest of systems engineering as well.

Another closely related area is information science. Washington State University defines information science as follows:

> "Information Science seeks to understand the theory and techniques by which information is encoded, stored, communicated, transformed, and anlayzed. It further seeks to apply this understanding to the analysis and control of

complex goal-directed systems. In this effort it draws upon concepts from a wide variety of traditional disciplines such as mathematics, philosophy, economics and management science. In return it has applications to these and other disciplines."

The above quoted definitions of disciplines strongly interacting with systems engineering are but few examples of certain commonality of a large body of knowledge. Indeed, considerations based on the interaction and transaction of systems oriented disciplines do play an important role in defining the systems engineering program and its relation to other programs both in terms of academic content and its administration. This relationship and its impact on the program has been very lucidly and with great insight exposed by the faculty of the Systems Engineering Program at Texas A and M University in a memorandum, excerpts from which are quoted below:

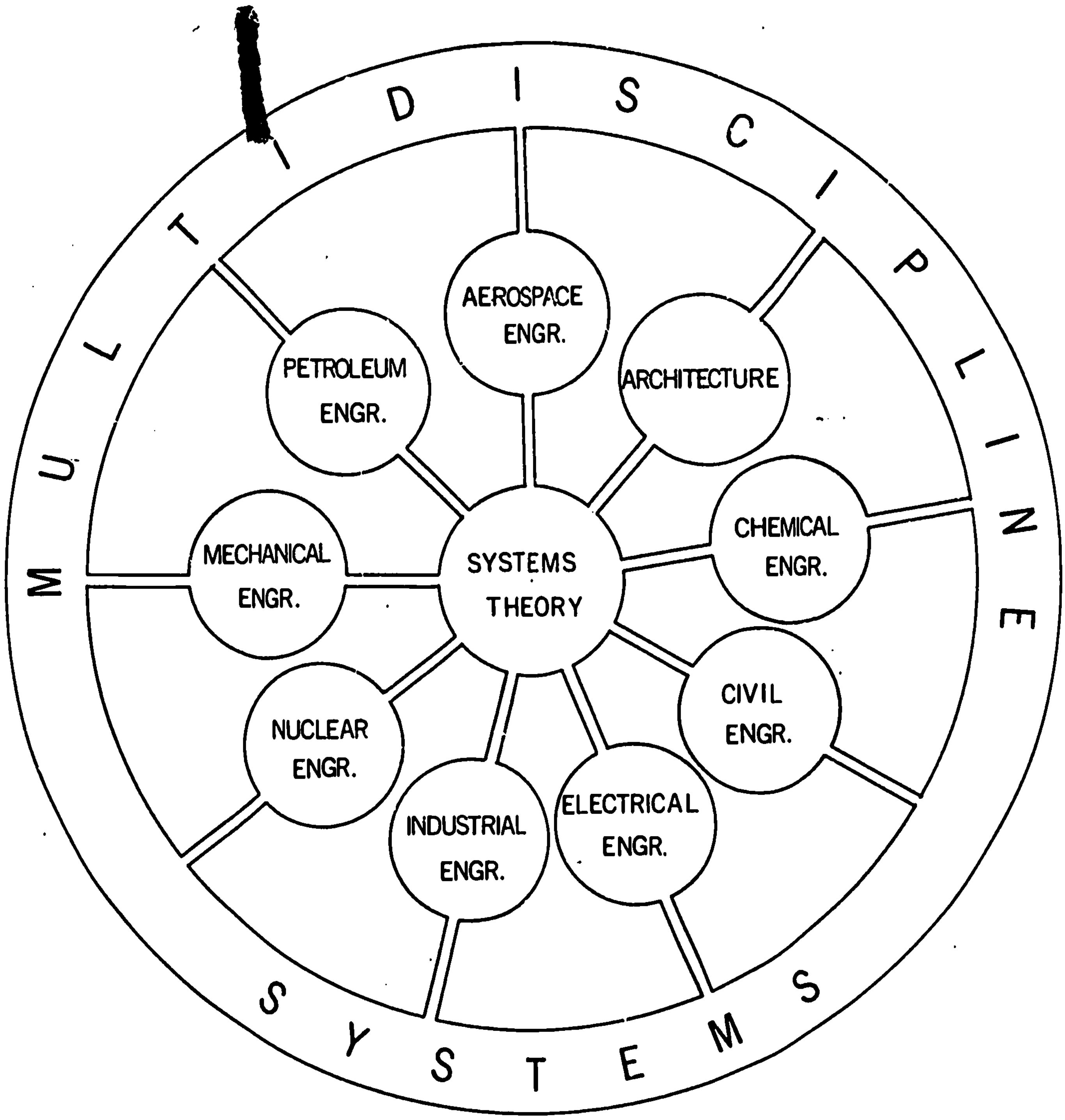
"The concept that we have been following in developing our systems engineering program can be illustrated by the diagram in Table 5. It is our belief that there are certain underlying principles and techniques which are common to all systems and therefore there exists a commonality in the basic systems theory that applies regardless of the nature of the system whether it be mechanical, electrical, civil, etc. This is represented by the central core of the diagram and it is this acitvity which forms the basis of our interdisciplinary program in systems engineering.

The disciplinary aspect of systems is depicted by the satellite group of professional disciplines such as we have at Texas A and M. Within each of these disciplines there are systems that are essentially peculiar of that discipline and in which a special expertise exists. For example, there are electrical engineering systems that are of special interest to electrical engineers and there are civil engineering systems of singular interest to civil engineers. Similarly, there are systems which, for all practical purposes, may be isolated in all the traditional disciplinary boundaries.

There are, of course, many systems which are multidisciplinary and which require the joint involvement of many fields. As an extreme, one might select the universe as his primary system. With this concept there would be a single system with which to concern ourselves. However, in the practical solution of problems, it is necessary to isolate systems (which we might call subsystems of the universe) for special attention. The outer ring of the diagram represents multidiscipline systems.

The concept of the diagram has much in its favor. First, it recognizes that there is some commonality of systems

Table 5. Concept of Interdisciplinary, Disciplinary and Multidisciplinary Aspects of Engineering and Architecture



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of all types. It offers an arena in which our Systems Engineering Center can develop course work, multidisciplinary research efforts, and other aspects of joint concern. However, it also allows each discipline to nourish and to cultivate those systems which are of primary interest to that group and which have little if any interaction with the other disciplines. Second, no discipline is legislated; when more than one discipline exhibits an interest in a given activity, that activity automatically falls in the outer ring of the diagram. Third, since systems theory has different implications in different fields, each field is allowed to exploit the general resource of systems theory in treating the peculiarities of its particular problem.

It is our opinion that it is not accurate to state that one who has a knowledge of the general aspects of system theory is automatically equipped to attack all engineering problems. We blieve that the good systems engineer not only is well grounded in systems theory, but also has a sufficient knowledge of his engineering field to interrelate properly various subdisciplines and has at least an awareness of the application of systems theory in other disciplines so that he can capitalize on analogies with those disciplines.

Thus we view systems engineering as a meeting ground for specialists form various disciplines, and a systems engineer as a specialist in a specific discipline, who is also trained in systems theory.

Within the general framework of the structure of academic disciplines, the relationship between systems theory, conceived as a theory of abstract mathematical models of systems, and mathematics itself needs to be clarified in greater detail. On this subject we quote Mesarovic [30]:

"The basic objects of study in mathematics are sets, i.e. families of elements collected together according to some properties. The various branches of mathematics differ principally in the additional structure the sets under consideration have, i.e. in the additional properties considered. Set theory deals with the relations among sets and sets of sets and without assuming a great deal of addition structure. In algebra, one considers sets on which are defined certain functions which are (normally) closed in the sets. In topology, a family of subsets in each set provides the basic structure. If the sets are sufficiently structured, then their elements are called numbers and the structure is called numerical structure.

In systems theory, one uses material from many different branches of mathematics. Actually, it is the type of properites which are observed in the real system that determines which

branch of mathematics is appropriate. If the understanding of the phenomena is minimal, a model of the system can be built by using set theory. With some better understanding of the structure of the real system one can use algebras, logic, topology, etc. If the results of the observation or experimentation are quantitative, one can exploit number-theoratic mathematical systems such as difference equations, recursive functions, differential equations, etc. It is very important to realize that mathematics has very broad range of tools, concepts and methods which can be used for the formal specification, i.e. modeling of various types of properties that might be called regular.

To summarize, whenever one reasons, contemplates or is developing a theory about a real system, one is doing this via a model or image of the system. It is this image which provides the basis for one's thinking about the real system. The main addition that systems theory can contribute to this fundamental process is the formalization of the model used. This formalization is accomplished by using mathematical structures. In view of the mentioned richness of the tools which the mathematics possesses, this is a healthy task. Actually, it is fair to assume that this formalization can be crucial for the clearer understanding of the model used. It can prevent many pitfalls. One might argue that any theory of real systems is based on the appropriate formal (mathematical) models although this fact traditionally has not been brought clearly into the open.

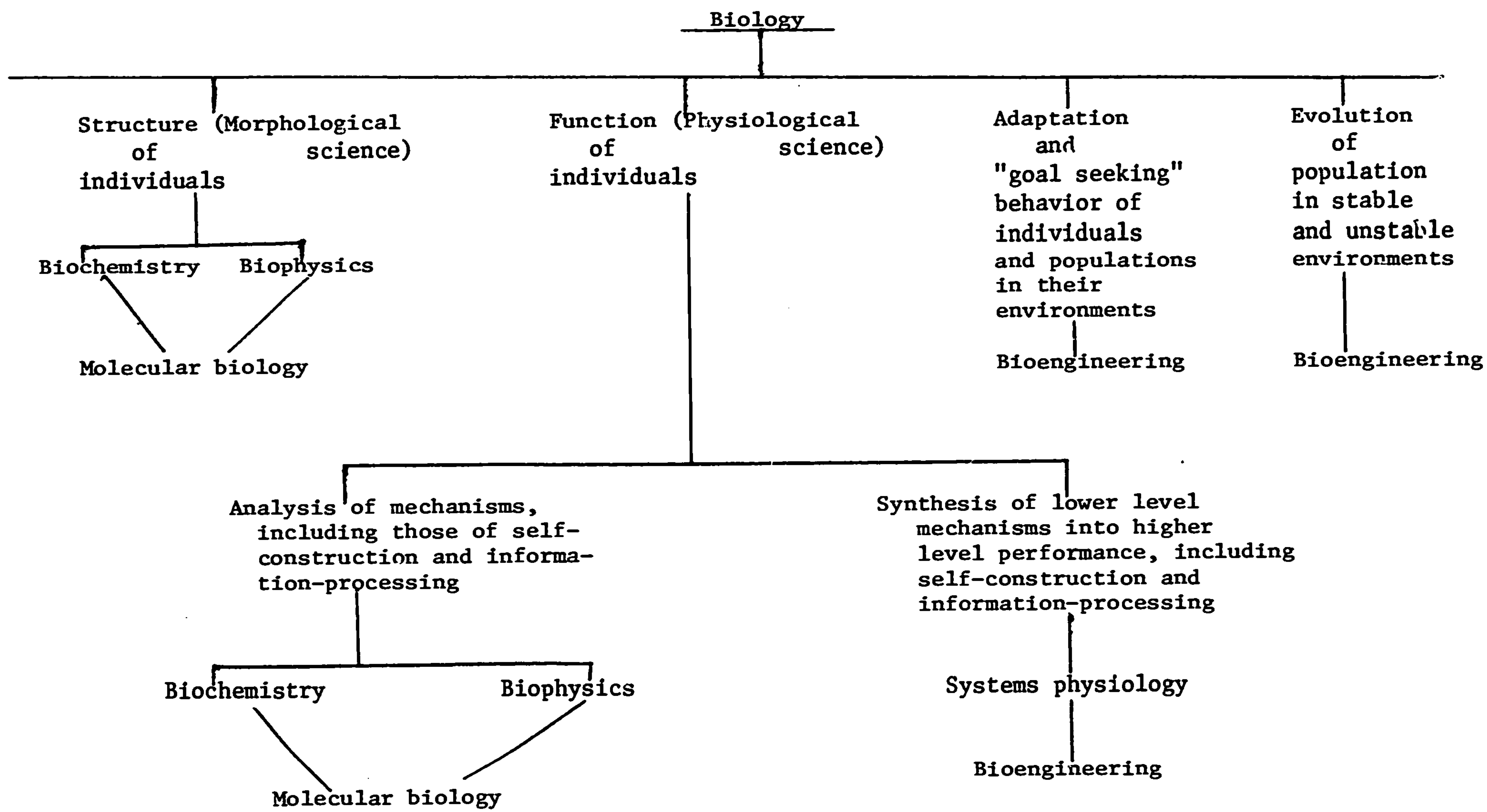
To repeat then, systems theory is the theory of formal, mathematical models of real or conceptual systems. Reference to the existing systems is crucial here. This is precisely where systems theory differs from pure mathematics. The latter studies abstract structures per se, the former only with reference to the real systems and in terms of the concepts and notions of the real systems (e.g. input, output, stability, adaptation, learning, etc.). The importance of the properties of the abstract system depends upon their meaning in the real system. The distinction here is not unlike the distinction between the network theory and mathematics or between the optimization and prediction theories and mathematics or even between mathematical physics and mathematics." [30].

We have stated on several preceding occassions that there is no reason to view all systems as being interdisciplinary in nature, even though many of them are such. But there are also a good many systems which are in the domain of a single discipline and we had examples of such systems, too. And since there are systems which are of primary interest to only one discipline, a point is reached in the development of the discipline when need arises to delimit the area of systems science

and engineering applications form other subject matter areas of that discipline. We shall take biology and systems physiology, which is a specialized branch of biology, as an example. A proposed structure of major subdivisions of biology is shown in Table 6. Within this structure, the central concept of systems physiology is that an arrangement of biological conponents, coupled, connected and interacting, has properties beyond the sum of those to be found in the components individually. For a more detailed explication of systems physiology and its relation to other branches of biology, we quote [34]:

> "Systems physiology is the science of the dynamic properties of connected, coupled, interacting components. The properties of a system of connected components depend upon: (1) the nature of the components individually, (2) the nature of the individual connections and coupling relations, and (3) the arrangement of components and the paths of communication among them. These system properties by definition lie outside the scope or competence of molecular biology and represent the province of systems physiology in which the structural integrity of components is accepted into experimental design and the dissolution of structure is minimized. Systems physiology emphasizes those attributes that define a system as living.
>
> Systems physiology poses the questions and sets the goals for analytical biology generally. According to this view, systems physiology is revealed as a science appropriate to many levels of organization in biology. It is characterized by its point of view, by the kinds of questions it asks, and the kinds of answers it seeks, rather than by the level of organization at which a study is made. Thus, systems physiology defies classification in the terms suggested by Medawar. The power of the systems viewpoint lies precisely in its general applicability for many levels of organization in biology, and in its emphasis on the characterization of detailed mechanisms and their incorporation into dynamic performance at higher levels.
>
> A major objective of systems physiology is the determination of properites and arrangements of components and signal pathways that give rise to the conspicuous functional attributes of a higher level system and the rationalization of these dynamical systems attributes in terms of the component properties and pathways of connection and coupling.
>
> An overall system is considered "animate" when it reveals the capacity to sustain itself in a state in which observable processes occur without causing the system itself to follow a path toward general mechanical, chemical, thermal and electrical equilibrium for the processes observed. According to this view, some animate systems of physiological interest are composed of connected inanimate systems, in which instance the animate state, or "life" is itself revealed as a systems property. In other

Table 6. Branches of Biology



instances the system of physiological interest is composed of connected, animate subsystems, in which case the overall system is a "higher form" of life. "Life" in either case is a system attribute ultimately, and not an attribute of molecular components. In this strict sense, systems physiology is above all "life science"."

We shall conclude this section witha comment by J. M. Briggs, Director, Civil Engineering Systems Laboratory, M.I.T., on the interaction of systems and civil engineering [8]:

"Civil engineering involves the planning, design, and construction of large facilities. All of these require a systematic approach to ensure both the adequacy and economy of the final product and the efficiency of the engineering process itself.

The word "systems" is used here in its broadest sense to include large constructed facilities, the operation of which involves the complex interaction of many parts. Familiar examples are transportation systems and water resource systems. The earliest application of formal systems analysis in the civil engineering field was probably in these areas. Another early application was in construction management, where the system is not physical but rather a series of operations. A more recent use of systems analysis, not yet fully developed, is in structural design where the structure and its loading are considered to be an operating system governed by the laws of probability.

Systems analysis draws upon discipline areas which were not previously considered to be a part of civil engineering. These include operations research, mathematical programming, stochastic processes, computer technology, and decision theory. It is now apparent that civil engineers should be reasonably familiar with these subjects, and those with a special interest in systems should master them in depth. However, it would be a mistake to consider systems as a new branch of civil engineering with its own specialists. Systems analysis is meaningful for civil engineers only when applied to one of the traditional areas of civil engineering. For successful application, the engineer must have an intimate knowledge of one or more of these areas. In education, a program emphasizing systems analysis is appropriate only if the student is well-grounded in one of the application areas, such as water resources, transportation, or structures."

3.7 Role of Research in Systems Science and Engineering Programs

The interrelationship between systems science and engineering as academic disciplines and academic research in systems is more intimate and significant than in the traditional disciplines. There are two main aspects of this relationship which need special consideration, i.e.

(1) Research as a source of new knowledge for the development of systems science and engineering as a discipline.

(2) Organization of research as team effort for handling significant systems problems.

With respect to the first item, research efforts should concentrate on the theory of systems and systems engineering methodology since in these areas the understanding is least advanced and the system science and engineering curricula are weakest. Concentration on this aspect of research is essential for further development and strenthening of systems science and engineering programs.

With respect to the second item, an increasing number of educators recognized that an improvement in doctoral research that would benefit society would be the encouragement of team research.

> "Most of the important problems facing the United States today require concurrent study in several fields. The emphasis on individual doctoral work often leads candidates to overlook important considerations in adjacent areas. Several candidates working as a team on an interdisciplinary problem would produce results many times as valuable as the sum of their individual works. Experience from the graduate project courses indicates that there is no danger of being unable to assess the contribution of each member of such teams. If team-applications theses are a part of the university's doctoral program, the university will serve a much more valuable role in helping society than it does today [28]."

Although the need for academic research activities in systems is obvious, the main obstacle to its implementation is often the fact that research in systems science and engineering cuts across the traditional boundaries of many disciplines and does not fit traditional departmental organization of an academic institution. Most academic institutions are still in search for a solution to this problem. Often the solution is sought by establishing research centers and laboratories for spon-

sored research with staff recruited from various departments. Again, in some cases these centers or laboratories have no staff of their own, but provide only the means of communication and cooperation between the traditional groupings within the institution. Unfortunately, however, these solutions prove to be poor substitutes for an academic institution being too inflexible or short-sighted to adapt itself to the new operational and social environment.

3.8 Academic Institutions Offering Systems Programs

During the sixties, systems engineering has become formally established as an academic discipline. Prior to 1960, to the best of our knowledge, only the University of Pennsylvania and the University of Arizona had formally organized programs in systems engineering, the first since 1953, the latter since 1959. In 1970, there were at least 44 institutions offering degrees or options in systems science or systmes engineering of which many were degree granting programs. Of these, three programs were accredited by the Engineers Council for Professional Development, among them the programs of the University of Florida and Southern Methodist University. The fourth, the systems engineering program of Boston University, was in the process of accreditation.

The organizational structure and the administrative status of system science and engineering programs in academic institutions shows considerable variation and often reflect the actual pattern of the development of the program in a particular institution. In some instances the starting point for the development of the program was the school or department of electrical engineering. This was where the program originated in the University of Pennsylvania for example. And although the Systems Engineering and Operations Research Program at the University of Pennsylvania is now an interdepartmental program covering broad systems aspects of engineering and engineering management, it still has strong personal and administrative links to the More School of Electrical Engineering which initiated the program approximately a decade ago. In other instances, schools or departments which started the development of systems science and engineering programs were schools of industrial engineering, mechanical engineering, or civil engineering.

With respect to the organizational status in the academic institutions, systems science and engineering programs can be classified into two major categories, i.e.:

(A) Programs offered by Systems Science and Engineering Departments

(B) Interdepartmental or Intradepartmental Systems Science and Engineering Programs

Table 7 gives a list of institutions offering systems science or

Table 7. Administrative Status of Systems Science and Engineering Programs in Academic Institutions

A. Institutions with Systems Science and Systems Engineering Departments

1. Air Force Institute of Echnology, Dayton, Ohio.
2. University of Arizona, Tucson, Arizona.
3. Polytechnic Institute of Brooklyn, Brooklyn, N.Y.
4. University of California, Los Angeles, California.
5. Case Western Reserve University, Cleveland, Ohio.
6. Univeristy of Florida, Gainesville, Florida.
7. University of Illinois, Chicago, Illinois.
8. University of Miami, Miami, Florida.
9. University of Pittsburgh, Pittsburgh, Pennsylvania.
10. Rensselaer Polytechnic Institute, Troy, New York.
11. Southern Methodist University, Dallas, Texas.
12. Stanford University, Palo Alto, Oalifornia.

B. Institutions with Interdepartmental or Intradepartmental Systems Science or Systems Engineering Programs.

1. Boston University, Boston, Massachusetts.
2. Carnegie-Mellon Univeristy, Pittsburgh, Pennsylvania.
3. Columbia Univeristy (EE), New York, New York.
4. Cornell Univeristy, Ithaca, New York.
5. Georgia Institute of Technology, Altanta, Gerogia.
6. Harvard University, (EE), Boston, Massachusetts.
7. J. Hopkins University, Baltimore, Maryland.
8. Univerity of Houston, Houston, Texas.
9. Massachusetts Institute of Technology, Boston, Mass.
10. Miami University(Apl.S.), Oxford, Ohio.
11. Michigan State University, Lansing, Michigan.
12. University of Michigan (EE), Ann Arbor, Michigan.
13. University of New Mexico, Albuquerque, New Mexico.
14. State University of New York (EE and ME), Buffalo, New York.
15. Northwestern University (OR and IE), Chicago, Illinois.
16. Oakland University, Rochester, Michigan.

17. Ohio University, Columbus, Ohio.
18. University of Oklahoma (Eng.), Norman, Oklahoma.
19. P.M.C. Colleges, Chester, Pennsylvania.
20. University of Pennsylvania (EE), Philadelphia, Pennsylvania.
21. Portland State University, Portland, Oregon.
22. Princeton University (EE), Princeton, New Jersey.
23. W.M. Rice University, Houston, Texas.
24. San Jose State College, San Jose, California.
25. Syracuse University, Syracuse, New York.
26. Tennessee Technical University (EE), Cookeville, Tennessee.
27. Texas A. & M. University, College Station, Texas.
29. University of Toledo, Toledo, Ohio.
30. Union College, Schenectady, New York.
31. Washington University, St. Louis, Missouri.
32. Wright State University, Dayton, Ohio.

engineering programs, broken down by the type of administrative structure of these programs. The first category includes institutions which have systems science and engineering departments as distinct administrative units. There were 12 such institutions, some of which have systems science or engineering departments jointly with some other discipline, for instance, industrial engineering. The second category consists of 42 institutions which either have systems programs on the institutional level without departmental status, or have systems science and engineering programs included in one of the traditional departments such as electrical engineering or industrial engineering, or have interdepartmental systems programs supervised by an interdepartmental committee or a similar body which is responsible for the overview and coordination of the program. These interdepartmental committees might or might not have other administrative responsibilities beyond those of coordination and advising.

Table ? lists the same institutions by program levels and degrees offered. Of the total number of 46 institutions, 15 institutions have undergraduate systems science or engineering programs, 35 institutions have programs leading to the Masters of Science or Masters of Engineering degree in systems science or engineering, and 29 institutions have programs leading to the Ph.D. degree. Hence, there is a significant prevalence of graduate programs over the undergraduate program at this point of development.

Table 8. Institutions by Systems Science or Engineering Program Levels and Degrees Offered

Institution	B.S.	M.S. or M.Eng.	Ph.D or Dr. Eng.
Air Force Inst. of Tech		X	
University of Arizona		X	X
Boston University	X	X	
Poly. Inst. of Brooklyn	X	X	X
UCLA	*	*	*
Carnegie-Mellon U.			*
Case Western Reserve		X	X
Columbia University		*	*
Cornell Univeristy		*	*
Univ. of Delaware	*	*	*
Univ. of Florida	X	X	X
Georgia Tech	*	*	
Harvard University			*
University of Houston		*	
J. Hopkins Univ.			*
University of Illinois	X		
Univeristy of Miami	X	*	
Miami Univ.	X		
U. of Michigan		X	X
Michigan State Univ.	*	X	X
U. of New Mexico		*	*
S.U. of New York		*	*
Northwestern Univ.		*	*
Oakland Univ.		X	
Ohio University	X	X	
U. of Oklahoma	*		
U. of Pennsylvania		X	*
U. of Pittsburgh		*	X
P.M.C. Colleges		X	
Portland Univ.	*	*	X

Table 8.. (continues)

Institution	B.S.	M.S. or M.Eng.	Ph.D. or Dr. Eng.
Princeton Univ.	*	*	*
Rensselaer Polyt. Inst.		X	X
Rice Univ.			*
San Jose St. C		X	
South Methodist Univ.	X	X	X
Stanford Univ.		X	X
Syracuse Univ.		X	X
Tennessee Tech Univ.		X	
University of TExas		*	*
Texas A&M Univ.		X	X
Univ. of Toledo			*
Union College	X	X	
Washington Univ.		*	*
Wright State U.	X	X	

Note: X indicates Systems Science or Engineering degree
* indicates systems option within another degree

3.9 Status of Systems Programs and Institutional Structure

The emergence of systems science and engineering as academic disciplines, together with the emergence of such disciplines as information science, biomedical engineering and others which cut across the lines of traditional classification of academic curricula in science and engineering, exposed the inadequency of college structures based on traditional subject matter classifications.

It is now apparent that, for one thing, a new bilateral interface must develop between the college of engineering and other colleges in the American university. The college of engineering can no longer be regarded as an appendage to the university system, receiving from, but not contributing to, the educational programs of the other colleges. On the other hand, engineering colleges must identify and make available to other programs relevant theories and techniques in such a way that their applicaitons are evident and meaningful in context of interdisciplinary problems.

In some institutions there is perhaps sufficient freedom and flexibility already in the academic and administrative frameworks of existing colleges to foster such an evolution. In other cases, the image of one college as held by another is so sterotyped and the curricula so rigidly structured as to preclude such major changes within the foreseeable future. If this is indeed the case, then perhaps the solution is to find a neutral ground outside of the framework of any given college which will attract, out of the existing colleges, an effective interdisciplinary research and educational team responsible for producing the new intellectual professional and practitioner.

Taking the above mentioned things into consideration, some of the more progressive colleges of engineering, such as University of Illinois or University of California, organized their departments along the subject matter division of systems, information, energy, and materials. This gives considerably more flexibility in setting up and operating interdisciplinary programs in general and systems science and engineering programs in particular, even thought it might not completely eliminate departmental parochialism.

Changes in administrative structure of educational institutions are also needed to promote interdisciplinary research, on which further development of systems science and engineering so much depends. We quote in this connection the relevant remarks of Lusignan and Hafferty [28]:

> "If interdisciplinary research takes place, interdepartmental grants or contracts must have some place to go. In the past, institutes have been set up to serve such a role. However, the typical institute has only remained interdepartmental for a short time. Very quickly such groups tend to form a permanent identity, obtain a series of grants, find a permanent faculty and faculty head, and in normal progression become a department. While this is a good way to modify department boundaries, it does not actually provide a home for truly interdepartmental research, since the members become experts in one new area rather than remain a group of experts from different areas.
>
> What is needed is a service within a university's central administration that catalogs sources of funds for interdisciplinary research, lists researchers in different departments, provides letterheads and administrative support for proposal and report writing, and brings to department heads' attention the importance (with respect to promotions) of the faculty's undertaking such research. Under such an umbrella, faculty from different departments can get together to undertake research of an interdisciplinary nature. When a project is finished, they can disband, regroup, or do whatever is appropriate for further projects. Since they join only for the project, the faculty would be primarily members of their own departments and thus would remain experts in their different fields. Several different groups on different projects could be formed at the seme time, and it is even probable that some of the more active faculty could be members of more than one team at any one time. To some the interdepartmental research unbrella may sound like an innovative proposal. However, those acquainted with the space industry will recognize it as the equivalent of the vertical (department) organization, but have lacked the horizontal (project) organization. It is this dual organization that has allowed the space industry to solve the highly complex problems of the space age. If it as the equivalent of the vertical and horizontal management structure that all large firms use today. The univer sities have long had the (department) organization, but have lacked the horizontal (project) organization. It is this dual organization that has allowed the space industry to solve the highly complex problems of the space age. If the universities are to meet the challenge of the complex social and technical problems of today's world, they must develop the administrative mechanism to allow their many experts to work together on interdisciplinary projects."

Experience with interdisciplinary team projects on the teaching and research level have demonstrated the power and relevance of such an approach. However, much home work is necessary before its full weight of the systems approach can be brought to bear upon the problem of the educational institutions which are expected to teach this very approach.

CHAPTER 4. ANALYSIS OF THE CORE AND ORIENTATION OF SYSTEMS PROGRAMS

4.1 Subject Matter Coverage of Systems Science and Engineering Programs

An attempt to make an inventory of courses contained in or related to systems science and engineering programs in academic institutions was made by Vidale in 1969 - 1970. He proposed an a-priori classification of typical courses in systems science and engineering, grouping these into three major categories and 15 subcategories as shown below [47]:

- 1.0 Interdisciplinary Theory
  - 1.1 Mathematical Foundations
  - 1.2 Theory of Systems Structure
  - 1.3 Stochastic Theory
  - 1.4 Optimization Theory
  - 1.5 Control Theory
  - 1.6 Communication Theory
  - 1.7 Cybernetic Theory
- 2.0 Interdisciplinary Technology
  - 2.1 Simulation and Experimentation
  - 2.2 Systems Design Methodology
- 3.0 Applications
  - 3.1 Hardware Systems
  - 3.2 Biological Systems
  - 3.3 Socio-Economic Systems
  - 3.4 Ecological Systems
  - 3.5 Computer-Information Systems
  - 3.6 Operations

The proposed grouping of courses according to the above classifications schedule is given in Table 9. It should be noted that the three major categories are viewed as interdisciplinary, whereas most of the subcategories are not. A course was assigned by Vidale to one of the three interdisciplinary categories only if it did not fit into a subcategory.

Data on the available courses in the institutions surveyed, arranged according to the above classification schedule, is reproduced in Table 10. We quote Vidale's comments on this data:

> "The most vexing problem is classification of courses that cover more than one category. My solution was to assign each course to a category and then ask each institution's program chairman to check this; 26 responded by verifying or modifying the course count and in some cases by assigning courses to more than one category. In these cases, the course was counted as 1/2 course if placed in two categories, 1/3 course if place in three categories, etc.

Table 9. Classification of Typical Courses in Systems Science and Engineering Programs

1.0 Interdisciplinary Theory
- General System Theory
- System Analysis
- Foundations of Systems Science
- Linear Systems
- Nonlinear Systems
- Dynamic Systems
- Distributed Systems

1.1 Mathematical Foundations
- Modern Algebra
- Linear Algebra and Matrices
- Topology
- Complex Variables
- Integral Transforms
- Vector Calculus
- Functional Analysis
- Differential Equations
- Mathematical Logic

1.2 Theory of System Structure
- Topology of Systems
- Graph Theory
- Flow in Nets
- Sensitivity Theory
- Multi-Level System Theory
- Network Theory

1.3 Stochastic Theory
- Probability and Statistics
- Stochastic Processes
- Reliability Theory
- Statistical Decision Theory

1.4 Optimization Theory
- Calculus of Variations
- Dynamic Programming
- Linear and Nonlinear Programming
- Direct Methods

15. Control Theory
- Feedback Control System Theory
- Stability Theory
- Optimal Control
- Nonlinear Control Systems
- Sampled-Data Control Theory

1.6 Communication
- Information Theory
- Coding Theory
- Signal Theory
- Detection and Estimation Theory

1.7 Cybernetic Theory
- Arificial Intelligence
- Pattern Recognition
- Adaptive and Learning Systems
- Cybernetic Machines
- Synthetic Behavior Systems
- Mathematical Theory of the Human Operator
- Man-Machine Systems

2.0 Interdisciplinary Technology
- Systems Engineering
- Systems Simulation and Synthesis
- Systems Design
- Simulation & Optimization Methods

2.1 Simulation and Experimentation
- Numerical Analysis
- Analog and Hybrid Simulation
- Digital Simulation
- Modeling and Identification
- Design of Experiments
- Instrumentation
- Systems Laboratory

2.2 System Design Methodology
- Problem Definition
- System Evaluation
- System Integration
- Design for Reliability and Maintainability
- Computer-Aided Design
- Large-Scale System Design
- Systems Management
- Engineering Economic Analysis

Table 9. (continued)

3.0 Applications
- Applications of Engineering Models
- Applications of Control and Systems Theory
- Systems Analysis Applications
- Project
- Special Problems

3.1 Hardware Systems
- Control and Communication Systems Synthesis
- Circuit Analysis and Synthesis
- Utilities
- Vehicle Systems
- Computer Hardware
- Energy Conversion Systems

3.2 Biological Systems
- Organic Systems
- Bio-Engineering Models
- Cognitive Processes
- Man-Machine Systems
- Neural Nets
- Human Factors Engineering
- Biological Control Systems
- Bio-systems

3.3 Socio-Economic Systems
- Economic Theory
- Game Theory
- Utility Theory
- Urban Systems Analysis
- Decision and Value Theory
- Forecasting

3.4 Ecological Systems
- Environmental Systems Engineering
- Water Resource Systems
- Eniironmental Bio-technology
- Urban Environmental Engineering

3.5 Computer-Information Systems
- Programming Languages
- Systems PRogramming
- Logic Design of Computers
- Automata and Switching Theory
- Real-Time Systems
- Information Systems Engineering
- Discrete Systems

3.6 Operations
- Operations Research
- Industrial Engineering
- Transportation Systems
- Inventory Control Systems
- Quality Control Systems
- Queue Theory
- Industrial Dynamics

> The subject matter profiles provide a rough but concise indication of subject areas emphasized in each program, emphasis on theory vs. applications, and extent of converage in each category (though the horizontal or vertical nature of the coverage is not protrayed explicitly). The Institution Totals aid in determining relative emphasis within each program and do not necessarily reflect the size of the administrative units (departments, divisions, standing committees, etc.). The Category Totals provide a measure of the composite emphasis for each category. It is not intended to suggest a "model program," with courses offered in the indicated proportions. Furthermore, it is not implied that all subject areas must be covered in a curriculum. It is a rare department--even university--that can cover all these subjects in depth."

Even though data contained in Table 10 is in many useful ways indicative of the existing system science and engineering programs, it was not sufficient for a more detailed analysis aimed at answering such questions as what is the common core of science programs in terms of subject matter coverage, what are their relative orientations with respect to such a core etc. We shall address ourselves to these topics in the sections which follow next.

Table 10. Subject Matter Profiles in Systems Science and Engineering Programs

Institution	Interdisciplinary Theory	Mathematical Foundations	Theory of System Structure	Stochastic Theory	Optimization Theory	Control Theory	Communication Theory	Cybernetic Theory	Interdisciplinary Technology	Simulation and Experimentation	System Design Methodology	Applications	Hardware Systems	Biological Systems	Socio-Economic Systems	Ecological Systems	Computer Information Systems	Operations	PROGRAM TOTALS
Air Force I.T.	1	0	0	5	1	0	1	0	1	0	4	0	3	1	1	0	1	1	20
*U. of Arizona	7	0	0	4	2	0	0	1	1	4	2	2	0	6	0	0	10	9	48
*Boston U.	4	9	0	5	2	3	1	0	0	5	6	0	4	0	2	0	8	3	52
*P.I. of Brooklyn	12	4	1	14	4	10	2	1	2	13	6	0	3	5	8	0	13	21	119
UCLA	4	9	2	7	7	11	6	3	0	6	4	0	6	4	2	7	18	5	101
*Carnegie-Mellon U.	0	7	0	0	2	5	2	1	0	1	0	0	0	0	0	0	8	1	27
Case Western R.	5	0	0	0	1	6	0	0	1	0	0	0	0	0	0	0	2	0	15
Columbia U.	4	1	7	2	2	4	6	1	0	2	0	0	5	0	0	0	1	0	35
*Cornell U.	0	0	1	4	4	0	0	0	0	2	3	0	0	0	5	4	0	10	33
U. of Delaware	1	3	0	3	4	0	1	0	2	3	0	0	4	0	0	0	0	2	23
*U. of Florida	2	26	0	15	7	10	2	0	5	16	8	0	4	0	9	0	11	12	127
*Georgia Tech	10	0	0	3	1	0	0	0	2	3	2	2	0	0	0	0	0	0	23
*Harvard U.	5	5	2	5	7	7	0	1	0	2	1	2	0	1	3	3	4	3	51
*U. of Houston	0	4	0	1	2	2	0	0	1	3	5	0	2	0	0	0	7	0	27
*U. of Illinois (Chicago)	7	0	1	1	2	4	5	1	0	1	0	1	5	8	5	0	4	8	53
*U. of Miami	0	0	1	5	2	0	0	0	1	3	2	2	0	2	2	0	7	7	34
*Miami U.	2	2	0	2	2	0	0	0	2	4	1	1	0	0	0	0	3	4	23
*U. of Michigan	6	0	1	5	4	4	12	0	0	3	2	0	6	0	0	0	9	0	52
*Michigan St. U.	4 5/6	3	1 1/3	3	3	5 5/6	1	2	0	2 1/2	1	1 1/2	0	0	3	0	0	3	35
U. of N. Mexico	2	0	2	2	1	1	2	0	1	0	0	0	2	0	0	0	0	1	14
*Northwestern U.	2	0	0	0	0	0	0	0	2	1	1	0	0	2	0	0	0	0	8
*Oakland U.	1	2	0	1	0	1	0	0	0	0	1	2	0	0	0	0	3	1	12
*Ohio U.	1	0	1	4	3	1	0	2	3	1	1	1	0	3	1	0	1	3	26
*U. of Penn.	1 1/3	3	2 1/2	5	2	4 1/2	3	2	2 5/6	4 1/2	4 1/2	1 5/6	6	2	3	2	8	8	66
U. of Pittsburgh	2	0	2	3	3	3	2	0	0	5	5	0	2	1	1	0	7	5	41
PMC Colleges	2	2	0	0	0	0	0	0	2	0	2	0	4	2	0	2	2	0	18
Portland St. U.	3	6	1	7	0	3	0	0	3	4	0	0	0	0	8	0	0	2	37
Princeton U.	3	1	0	2	0	3	5	2	0	1	0	0	1	0	0	0	7	0	25
*Rensselaer P.I.	2	5	3	5	4	6	4	1	0	9	3	2	20	4	1	0	9	6	84
*Rice U.	3	14	0	4	7	4	3	0	0	3	1	0	2	1	6	0	10	0	58
San Jose St. C.	1	0	0	0	0	0	0	2	1	0	0	0	0	1	1	0	1	0	7
*St. Methodist U.	8	9	2	11	9	5	5	0	2	11	7	10	12	2	1	0	22	5	121
*Stanford U.	2	15	0	3	3	0	0	0	3	3	0	1	0	1	11	0	0	0	42
*Syracuse U.	1	4	1	2	2	0	2	1	1	3	0	0	0	1	1	0	11	1	31
Tenn. Tech. U.	4	0	0	1	0	1	0	0	1	1	0	0	0	0	0	0	0	0	8
*U. of Texas	5	0	1	3	5	5	4	3	0	2	0	0	0	0	0	0	16	1	45
[illegible] A&M U.	0	0	2	0	0	0	0	0	2	1	3	0	0	0	0	0	0	0	8
[illegible] of Toledo	9	23	1	4	7	5	4	1	1	6	3	0	12	1	0	0	4	10	91
[illegible]ington U.	4	12	0	11	5	3	4	1	0	3	2	0	4	1	0	0	2	0	52
*Wright St. U.	6	5	0	2	0	3	1	0	1	0	8	5	1	0	0	0	3	0	27
Category Totals	$137\frac{1}{6}$	174	$35\frac{5}{6}$	154	110	$120\frac{1}{3}$	78	26	$43\frac{5}{6}$	132	$80\frac{1}{2}$	$34\frac{1}{3}$	108	49	74	18	212	132	

4.2 Core Areas of Systems Science and Engineering Curricula

Since there is indeed a great variety of opinions on what constitutes systems science and engineering as an academic discipline, we made an analytic study of the field as it is reflected in actual academic programs. Specifically, the immediate goals of this analysis were

1. To identify the concept of systems science and engineering as an academic discipline in terms of topical coverage of relevant courses.

2. To extract from a representative sample the common core of existing systems science and engineering programs.

3. To evaluate the orientation of individual systems science and engineering programs in terms of a common core.

The emphasis of this phase of the study was on the methodological aspect of the procedure rather than actual evaluation. The basic data for the study were the descriptions of systems courses and programs as they appear in the catalogues of selected academic institutions.

These descriptions were taken from 1967/1968 catalogs of eighteen selected academic institutions which are listed in Table 11. Each of these institutions had either a formal, degree-granting program in systems science and/or engineering, or had a systems option in some related field, or otherwise had a strong overall curriculum orientation toward systems science and/or engineering. The programs chosen represented curricula available at one or more levels, offering either B.S., M.S., or Ph.D. degrees or all of them. The selected programs comprised a total of 445 courses, averaging approximately 25 courses per institution.

A number of the programs included in the study had diverse beginnings, the evidence of which was often still apparent from their present administrative affiliation--i.e., some systems programs had originated in, and are now affiliated with, the electrical engineering, mechanical engineering, or chemical engineering departments or schools. Administratively, the systems programs included in the study represented all of the principal methods of administrative organization: at some of the selected institutions, the systems program is a

Table 11. Systems Programs Selected for Content Analysis

Institution (Departmental affiliation in parentheses)	Abbreviation	Program Level B.S.	Program Level M.S.	Program Level Ph.D.
Air Force Institute of Technology	AF Inst		x	
University of Arizona	U Ariz		x	x
Boston University	Boston U	x	x	x
UCLA	UCLA	x	x	x
Case Western Reserve University	Case W		x	x
Cornell University (OR)	Corn		x	x
University of Florida	U Fla	x	x	x
Harvard University	Harv			x
John Hopkins University	J Hopk			x
University of Illinois, Chicago Circle	U Ill	x		
MIT (CE)	MIT		x	x
Miami University, Ohio (Apl. S)	Miami U	x	x	
New York University (EE)	NYU		x	x
University of Oklahoma	U Okla	x		
University of Pennsylvania (EE)	U Penn		x	x
University of Pittsburgh*	U Pitts		x	x
PMC Colleges	PMC		x	
Polytechnic Institute of Brooklyn	Brk Poly	x	x	x
Princeton University (EE)	Princt	x	x	x
Stanford University	Stanf		x	x
Tennessee Technological University (EE)	Tenn T		x	

* Bidisciplinary department

distinct administrative unit; at others the systems program is included in one of the traditional departments such as electrical or industrial engineering; at still others, the program is coordinated by some sort of interdepartmental committee.

It is clear from the different histories, orientations and administrative procedures that the selected programs are representative of the rich variety of an emerging discipline.

A combination of automatic keyword extraction and factor analysis techniques was used to identify the basic topical areas imbedded in the body of the sample set of 445 course descriptions. The complete descriptions of courses offered in the systems curricula of the institutions studied were keypunched for computer processing exactly as they appeared in their respective catalogs. The automatically extracted significant keywords were then manually edited to combine synonyms, etc. The edited list of keywords contained 149 distinct significant terms, which occurred more than 15 times.

For the factor analysis program, each of these 149 keywords was considered a variable, and each of the 445 courses was considered an observation. If a keyword appeared in the catalog description of a course it was assigned a value of 1; if not, it was assigned a value of 0. The factor analysis program produced two sets of correlations: one showing the relative importance of keywords to a factor, the other showing the relative importance of courses to that factor. The weights in the keyword/factor matrix were normalized to ranges from -1 to +1, and in some factors the negative values were high in absolute value while in others the positive values were high. No importance was attached to whether the high values for a factor were positive or negative. The subsequent rotation procedure produced a total of 14 significant factors, of which 12 could be meaningfully interpreted in terms of distinct subject areas.

The "meaning" of a factor was determined from the sets of keywords associated with it. Every keyword was assigned to one and only one factor, and when a keyword scored in more than one factor it was counted only for that factor in which its score was highest.

A list of the twelve interpreted factors, identified in terms of the corresponding subject area and ranked in order of importance, is

given in Table 12. Sets of significant keywords corresponding to each factor, with their scores, are given for each factor individually in Tables A1 through A14 in Appendix A.

We note from Table 12 that the subject area which ranks first in importance in the analyzed curricula of systems science and engineering, i.e., the factor with highest factor loading values, is signal processing. It covers signal flows in systems, information transmission and processing and related topics where the emphasis is on generation, transfer and utilization of information as opposed to matter or energy. This is in agreement with the prevailing opinion among scientists specializing in the systems area that signal processing is indeed one of the most important and characteristic aspects of systems theory and engineering. Other subject areas listed in Table 12 and the order of their importance also seem to be in line with the most recent developments in this discipline.

The next step in the analysis of systems curricula was to identify the most characteristic and relevant courses for each topic listed in Table 12. Naturally, the selection of courses was limited to the 445 courses which served as an input to this study. The basis for the evaluation of significance of these courses to each topic was the matrix which gives the relative importance of each factor to each course, called the factor score for the course. An attempt was made to relate each course to one and only one topic (factor) by using the highest score for the course. When all scores were low, the course was not placed in any factor. As we shall see, this fact can be meaningfully interpreted, too.

The titles of the first three courses which scored highest in each of the topics (factors) are listed in Table 13. The catalog description of these courses are given in Appendix E. Complete listings of courses (by titles only) which had significantly high scores in anyone topic (factor), arranged by factors, is given in Appendix B, Tables B1 through B12. All scores are shown in absolute value; the sign of the scores of a factor is the same as the sign of the weights of the keywords which characterize the factor. The code numbers refer to the course descriptions taken from the catalogues of the respective institutions.

Table 12. Significant Core Topics of Systems Curricula Identified by Factor Analysis of 445 Course Descriptions and Ranked by Importance

1. Signal Processing
2. Computer Systems
3. Theory of Switching Circuits and Automata
4. Control Systems
5. Optimization Theory
6. Engineering Economics
7. Theory of Games and Decision Making
8. Statistics and Experimental Design
9. Organic Systems and Human Engineering
10. Computer Systems Design
11. Numerical Analysis
12. Production Systems (Planning, Scheduling and Inventory Control)

Table 13. Listing of Courses Which Scored Highest on Each of the "Core" Topics (Factors)

Factor	Topic	School	Course Title	Score
1	Signal Processing	NY U	Methods of Noise and Random Process Analysis	6.87
		Case	Random Signals	6.33
		MIT	Random Signals and Linear Systems	5.99
2	Computer Systems	MIT	Management Information Systems	4.47
		Brk Poly	Computer Science	4.39
		Miami U	Introduction to Systems Analysis	4.26
3	Theory of Switching Circuits and Automata	Princeton	Theory of Switching Circuits and Automata	6.38
		U Penn	Switching Theory	5.77
		Princeton	Introduction to Computer Science	5.22
4	Control Systems	NY U	Feedback Control Systems and Servomechanisms	5.49
		Case	Modeling and Control of Physical Systems	4.46
		MIT	Control System Theory	4.17

Table 13. (continued)

Factor	Topic	School	Course Title	Score
5	Optimization Theory	NY U	Theory of Optimal Control Systems	4.62
		Princeton	Theory of Optimal Control	4.06
		Harvard	Mathematical Programming & Economic Analysis	3.82
6	Engineering Economics	Cornell	Engineering Economic Analysis	5.00
		UCLA	The Engineer in the Business Environment	4.96
		Cornell	Advanced Engineering Economic Analysis	4.75
7	Theory of Games and Decision Making	U Penn	Programming Languages	3.84
		Cornell	Introduction to Probability Theory	3.28
		U Pitts	Operations Research	3.26
8	Statistics and Experimental Design	U Penn	Statistics	5.90
		Cornell	Introduction to Statistical Theory	5.74
		J Hopkins	Introduction to Statistical Theory	4.99
9	Organic Systems and Human Engineering	MIT	Analytical Models for Processing of Sensory Inputs	3.83
		NY U	Research Methods in Human Factors	3.74
		U Penn	Seminar in Human Factors Engineering	3.72
10	Computer Systems Design	Cornell	Theory of Automata	5.79
		MIT	Computational Models	5.27
		NY U	Discrete State Machine Automata	3.95
11	Numerical Analysis	Cornell	Computer Applications of Numerical Analysis	5.57
		U Penn	Higher Mathematics in the Solution of Engineering Problems	5.39
		U Penn	Numerical Analysis for Computers	4.98

Table 13. (continued)

Factor	Topic	School	Course Title	Score
12	Production Systems (Planning, Scheduling, and Inventory Control)	U Pitts	Digital Systems Simulation	4.82
		MIT	Systems Engineering and Operations Research	4.51
		Stanford	Dynamic Probabilistic Systems	3.90

Table 14. Number of Courses with Significant Scores by Factor and School

School	FACTOR 1	2	3	4	5	6	7	8	9	10	11	12	No Factor	TOTAL
U PENN	3	4	3	2	2	4	3	2	2	3	5	0	5	38
U ARIZ	0	5	0	1	1	0	0	0	4	1	1	0	7	21
U FLA	0	0	0	0	0	0	2	0	5	0	0	1	14	22
BOSTON U	1	0	0	1	1	0	0	0	1	0	0	2	0	6
BRK POLY	1	2	0	3	1	0	0	2	1	0	0	3	8	21
AF INST	0	1	0	0	0	6	0	1	0	0	0	1	4	13
MIAMI U	0	3	0	0	0	1	0	0	0	0	0	0	7	11
TENN T	1	0	0	1	1	0	0	0	0	0	0	0	5	8
UCLA	0	0	0	1	1	3	0	2	2	0	1	0	9	19
J HOPKINS	0	0	0	0	2	3	1	2	1	0	0	2	7	18
CASE W	2	2	3	5	2	0	2	0	1	3	0	0	6	26
MIT	5	3	1	2	1	3	1	0	3	4	3	3	9	38
PRINCETON	9	2	5	4	1	0	2	0	0	0	1	0	2	26
CORNELL	0	10	2	0	2	2	2	4	1	5	3	4	15	50
STANFORD	0	2	0	0	2	4	1	2	1	0	2	3	21	38
HARVARD	0	0	0	0	2	0	1	1	0	0	0	0	3	7
NY U	3	7	1	4	2	1	4	6	6	3	0	5	18	60
U PITTS	0	0	0	0	1	1	1	2	0	2	0	2	13	22

Table 15. Factor (Topic) Scores by Factor and School

	FACTOR											UNIDENTIFIED FACTORS			
School	1	2	3	4	5	6	7	8	9	10	11	12	(13)	(14)	Total	Average
U. PENN	11.27	6.11	13.72	5.56	5.79	13.28	9.85	9.5	5.61	7.50	18.11	0	(2.59)	(2.34)	111.23	3.18
U. ARIZ	0	9.36	0	1.47	1.74	0	0	0	7.84	3.11	2.48	0	(8.36)	(0)	34.36	2.15
U. FLA	0	0	0	0	0	0	2.54	0	9.39	0	0	1.30	(1.01)	(0)	14.24	1.58
BOSTON U.	1.42	0	0	1.20	2.73	0	0	0	1.96	0	0	3.01	(0)	(0)	10.32	1.72
BRK. POLY	3.50	6.44	0	6.74	1.23	0	0	5.32	1.49	0	0	6.21	(5.41)	(3.65)	39.99	2.50
AF INST	0	1.76	0	0	0	12.38	0	1.86	0	0	0	2.09	(0)	(1.07)	19.16	1.92
MIAMI U.	0	7.04	0	0	0	4.43	0	0	0	0	0	0	(0)	(0)	11.47	2.87
TENN T.	1.41	0	0	2.12	3.13	0	0	0	0	0	0	0	(0)	(2.05)	8.71	2.18
UCLA	0	0	0	1.77	1.73	10.28	0	5.63	6.28	0	2.43	0	(0)	(2.19)	30.31	2.75
J HOPKINS	0	0	0	0	3.43	6.45	1.57	6.77	1.52	0	0	4.96	(2.31)	(0)	27.01	2.25
CASE W	8.0	4.33	10.01	13.88	4.71	0	4.67	0	2.42	8.00	0	0	(0)	(0)	56.02	2.80
MIT	21.75	9.58	1.24	7.86	2.71	7.81	2.72	0	7.97	13.80	8.43	9.21	(3.74)	(4.55)	101.37	2.98
PRINCETON	21.40	5.59	20.14	9.08	4.06	0	2.48	0	0	0	2.93	0	(0)	(0)	65.68	2.63
CORNELL	0	23.74	5.53	0	3.47	9.75	5.48	11.45	1.87	15.77	12.05	10.11	(1.67)	(1.60)	102.49	2.77
STANFORD	0	4.51	0	0	5.02	9.73	2.15	5.39	2.32	0	5.46	9.73	(2.87)	(7.45)	54.63	2.60
HARVARD	0	0	0	0	6.11	0	2.62	2.05	0	0	0	0	(0)	(0)	10.78	2.69
N.Y.U.	10.93	11.42	2.76	12.73	5.86	3.81	5.41	21.20	15.45	8.72	0	12.04	(6.66)	(16.56)	133.55	2.73
U. PITTS	0	0	0	0	3.48	2.77	3.26	5.68	0	4.78	0	8.19	(1.52)	(1.25)	30.93	2.81

The results of the factor analysis were used to classify the programs in the various schools in the following way. A count was made of the number of courses from each school with significant factor scores for each factor. As can be seen from Table 14, the programs vary widely in their orientation. Some schools, such as the University of Pennsylvania and Cornell University have at least one course in nearly every factor. Others, such as Tennessee Technological Institute and Harvard University are more specialized in their orientation, having no courses in many of the factors. In order to further study the orientation of the programs, the factor scores of the courses relevant to the various factors were summed for each school for each factor. A total score for each school was obtained by summing the scores of all courses for that school relevant to any of the factors. Because it was felt that the number of courses might unduly affect the score, the average score for each school was claculated by dividing the total score by the number of courses for the school. This data is given in Table 15.

Using this technique to judge the relevance of each of the courses to a given factor, it was possible to draw a profile of a school's orientation with respect to the established core of systems programs by determining the number of courses offered by the school on a given core topic (factor) and calculating for every program the cumulative score per factor.

Table 16 identifies the two schools which scored highest on each of the 12 factors, and Table 17 identifies the two factors in which each school scored highest. Complete rankings of schools by topics (factors) are given in Tables C1 through C12, Appendix C. In turn, complete rankings of factor by schools are given in Tables D1 through D18, Appendix D.

In order to assess an institution's overall program of systems science or engineering in terms of the extracted 12-factor core, a total score was obtained for each school by summing, for that school, the values representing the relative importance of its courses to the factors by the number of courses taught at the school. With this method, the schools ranked as shown in Table 18. Thus, the systems engineering program of New York University, based on the catalog

Table 16. Academic Institutions Scoring Highest on Each "Core" Topic (Factor)

Factor	Topic	High Scorers	
1	Signal Processing	MIT	21.75
		Princeton	21.40
2	Computer Systems	Cornell	23.74
		NY U	11.42
3	Switching Circuits & Automata	Princeton	20.14
		U Penn	13.72
4	Control Systems	Case	13.88
		NY U	12.73
5	Optimization Theory	Harvard	6.11
		NY U	5.48
6	Engineering Economics	U Penn	13.28
		AF Inst	12.38
7	Games and Decision Making	U Penn	9.85
		Cornell	5.48
8	Statistics and Experiment Design	NY U	21.20
		Cornell	11.45
9	Organic Systems & Human Engineering	NY U	15.45
		U Fla	9.39
10	Computer Systems Design	Cornell	15.77
		MIT	13.80
11	Numerical Analysis	U Penn	18.11
		Cornell	12.05
12	Production Planning & Control	NY U	12.04
		Cornell	10.11

Table 17. Implied Orientations of Systems Programs of Sampled Academic Institutions

School	Factors in which School Scored Highest	Score
AF Inst	Engineering Economics	12.38
	Production Systems	2.09
Boston U	Production Systems	3.01
	Optimization Theory	2.73
Brk Poly	Control Systems	6.74
	Computer Systems	6.44
Case	Control Systems	13.88
	Theory of Switching Circuits & Automata	10.01
Cornell	Computer Systems	23.74
	Computer Systems Design	15.77
Harvard	Optimization Theory	6.11
	Theory of Games & Decision Making	2.62
J Hopkins	Statistics & Experimental Design	6.77
	Engineering Economics	6.45
MIT	Signal Processing	21.75
	Computer Systems Design	13.80
Miami U	Computer Systems	7.04
	Engineering Economics	4.43
NY U	Statistics & Experimental Design	21.20
	Unidentified	16.56
Princeton	Signal Processing	21.40
	Theory of Switching Circuits & Automata	20.14
Stanford	Engineering Economics	9.73
	Production Systems	9.73
Tenn Tech	Optimization Theory	3.13
	Control Systems	2.12
U Ariz	Computer Systems	9.36
	Unidentified	8.36
UCLA	Engineering Economics	10.28
	Organic Systems & Human Engineering	6.28
U Fla	Organic Systems & Human Engineering	9.36
	Theory of Games and Decision Making	2.54

Table 17 (continued)

School	Factors in which School Scored Highest	Score
U Penn	Numerical Analysis	18.11
	Theory of Switching Circuits & Automata	13.72
U Pitts	Production Systems	8.19
	Statistics & Experimental Design	5.68

Table 18. Ranking of Institutions by Cummulative Factor Scores

1.	New York Univ.	133.55
2.	Univ. of Penn.	111.23
3.	Cornell Univ.	102.49
4.	M.I.T.	101.37
5.	Princeton Univ.	65.68
6.	Case Western	56.02
7.	Stanford Univ.	54.63
8.	Brooklyn Polyt.	39.99
9.	Univ. of Arizona	34.36
10.	Univ. of Pittsburgh	30.93
11.	U.C.L.A.	30.31
12.	John Hopkins Univ.	27.01
13.	Air Force Inst.	19.16
14.	Univ. of Florida	14.24
15.	Miami Univ.	11.47
16.	Harvard Univ.	10.78
17.	Boston Univ.	10.32
18.	Tennessee Tech.	8.71

descriptions of relevant courses, is closest to, i.e., most characteristic of, the 12 factor core of the sample set of systems programs. The system program of the University of Pennsylvania was next closest. Here, the rank of a school should be interpreted as the degree of goodness of fit of the institution's systems science and/or engineering program to the "model" program determined by the study.

By dividing the cumulative factor score for each institution by the number of systems courses taught at the instituiton, the average degree of relevancy of systems courses offered by the institution to the core program of most relevant courses was obtained. Under that method, the schools now ranked as shown in Table 19.

One further remark on the courses which scored very low on all of the twelve topics. Such an instance should be interpreted either as an indication that the course represents the beginning of a new contribution to or orientation of the subject area or as an indicator of a subject of quite marginal importance to the subject area. The investigation of the sample courses did in fact confirm that hypothesis. Examples of such courses were: "Transportation Management", "Maintenance Management", and "Communications Techniques", offered at the Air Force Institute; and "General Systems Theory". "Mathematical Systems Theory", and "Stochastic Control Theory", offered at Case-Western Reserve.

Thus, the course General Systems Theory, which is offered at the Case Western Reserve University, scored very low on the twelve factors and the analysis of the course disclosed that it indeed represents a new and unconventional development in systems area which cannot be mapped into traditional topics without significant residue. The same can be said about courses such as Mathematical Systems Theory (Case Western Reserve), Stochastic Control Theory (Case Western Reserve), or Communications Techniques (Air Force Institute).

Table 19. Ranking of Institutions by Average Score Per Relevant Course

1.	Univ. of Penn.	3.18
2.	M.I.T.	2.98
3.	Miami Univ.	2.87
4.	Univ. of Pittsburgh	2.81
5.	Case Western	2.80
6.	Cornell Univ.	2.77
7.	U.C.L.A.	2.75
8.	New York Univ.	2.73
9.	Harvard Univ.	2.69
10.	Princeton Univ.	2.63
11.	Stanford Univ.	2.60
12.	Brooklyn Polyt.	2.50
13.	John Hopkins Univ.	2.25
14.	Tennessee Tech	2.18
15.	Univ. of Arizona	2.15
16.	Air Force Inst.	1.92
17.	Boston Univ.	1.72
18.	Univ. of Florida	1.58

4.3 Alternative Model Curricula of Systems Science and Engineering

In this section, we shall describe other proposed model curricula of systems science and engineering for comparison with the core curriculum described in Section 4.2

Based on the analysis of the engineering curricula and courses offered at the University of California, Lost Angeles, Lifson and Kline proposed an undergraduate curriculum in systems design which is summarized in Table 20. The main features of the proposed curriculum are [27]:

" . The Design Process is introduced at the freshman level. In this course, the student performs a nontrivial design with emphasis on methodology, including the formulation and application of a value model.

. Experience with the freshman design course indicated the need for the early introduction to the student of probability and statistics and the use of the digital computer, in order to properly implement the Design Process. As a result, two half-courses covering these subjects are introduced at the beginning of the freshman year.

. Decision and Utility Theory and their application to Design are introduced at the junior level in the course in Economic Decision Theory.

. Senior design projects emphasizing methodology as well as design excellence are carried out in the senior Design sequence along with the exposition of the design methodology.

. An intensive experience in design in an engineering context is provided in the lower division by the design enrichment of the Statics-Strength of Materials courses.

. An introduction to the modeling process and the experimentation-test foundations of information procurement are offered in the sophomore Modeling and Measurement Laboratory.

. The applied humanities-social studies courses and stem are designed to provide the understanding of our social institutions necessary for the formation of menaingful value systems.

. The methods of analysis (mathematics) stem furnishes a language for modeling the real world and the methods for manipulating these models.

. The materials and science courses provide the bases for the evaluation of the physical realizability of our designs."

Table 20. Model Systems Design Curriculum (Undergraduate)
Proposed by Lifson and Kline

Years \ Stems	Mathematics Deterministic Distributed Parameters	Mathematics Deterministic Lumped Parameters	Materials and Science Energy and Matter Processing		Mathematics Probabilistic and Information Processing	Design and Laboratories	Humanities
1	Math Calculus		Chemistry	* *	Computer Probability & Stat		Applied Humanities
	Math Calculus		Chemistry	Physics Mechanics			Applied Humanities
	Math Calculus		Biochemistry	Physics Electr. & Mag.		*Introduction to Design	
2		Math Differential Eqs.		Modern Physics		Model & Measurement Lab.	Humanities
		Math Transform Theory		Materials		Statics-Strength * Design	Humanities
	Math Partial Dif. eq.	Deterministic Lumped Parameter			Information Dynamics	Statics-Strength Design	
3	Deterministic Distributed Parameter	Deter. Lump. Para Circuit Syn. and Feedback			Automatic Information Process	Exp. Engr. Lab.	
	Deter.Distr. Para. Diffusion Process	Deter. Lump. Para. Auto. controls		Physics Quantum Mech.		Exp. Engr. Lab.	
				Thermodynamics	Probabilistic Lumped Para. Signals & Noise	*Economic Decision Theory	Humanities
4				Thermodynamics	Probabilistic Lumped Para. Auto. Controls	*Design	Applied Humanities
	Deter.Distr.Para Wave Phenomena			Advanced Materials		*Design Lab.	Humanities
	Deter.Dist.Para. Solids Continuum Mech.		Biotechnology			*Design Lab.	Humanities

Note: * indicates courses in design stem.

We further quote the following additional observations and comments made with respect to the proposed curriculum.

"The modern computer has had a revolutionary impact on the practice of engineering. As a computational tool, both in analog and digital forms, and in its ability to process data in real time, the computer is replacing the slide rule as the engineer's primary calculation device. Compact keyboard and display consoles directly connected to a central processing unit are beginning to appear on engineers' desks in some of the larger companies and will be widespread in the next few years. The advantages of computer-aided design have been demonstrated. Applications of computer-aided design are appearing at an increasing rate.

The introduction of the computer as an engineering tool at the freshman level, therefore, is not only desirable, but also essential for an effective implementation of today's technology during the education process. The instructor in many engineering courses would then be able to cover material and assign problems which otherwise could not be handled (for example, use of the computer in structural analysis.) The student should be able to utilize the computer throughout his engineering education just as he formerly utilized the slide rule.

. Actual engineering problem situations in which the graduate engineer will find himself will inherently include considerations of an uncertain environment and uncertain results of design decisions. He will be dealing with uncertainty and nondeterministic measures. Therefore, a knowledge of statistics and probability (subjective as well as objective) is required. Basic concepts of this subject can also be successfully introduced at the freshman level, and can become part of the engineering student's tools available for use in other engineering courses.

. The lower division course, Introduction to Design, introduces the engineering student to the life cycle and the design process by means of active participation in a design project. Originally included in this course structure was a substantial amount of class time devoted to an introduction to the use of the computer and to engineering graphics in detail. This resulted in some crowding of the available time in which to carry out the design projects.

Some instructors prefer to have students work on individual projects on the same basic subject, such as an educational toy, thus introducing a competitive spirit in the class. Since the designs are submitted to a panel of judges for a design award competititon, this intoduces an incentive to the students to select their individual topics freely or from a large and varied list. In a similar manner, some instructors utilize student groups of five or so students working on fewer projects. This introduces the students to such real-world aspects of engineering as group organization, leadership,

communications within the group and contributive reporting, project breakdowns in small tasks, etc.

There is diversity of opinion among the faculty with regard to which way to operate the lower division design course. There are obviously good design learning-experiences in each of these methods, the success of the undertaking depending in large measure on the instructor's viewpoint and emphasis.

. The upper division design sequence introduces decision and value theory in the course on engineering economy in addition to the more traditional course content of interest and the time value of money, and the application to engineering investment and evaluation of alternatives. Principles of financial analysis are also taught in this course. This subject matter prepares the student for developing the evaluation criteria and decision structure of the design process.

. The senior design course stresses the design methodology in detail and particularly stresses concept formulation, system definition, and preliminary design activities. The students carry out paper design projexts using this methodology.

. The senior laboratory is the two-quarter design laboratory in which the students carry out design projects in greater detail, sometimes resulting in experimental models or prototypes.

In the past, these course have been taught independently and without integration. This has been in part because of administrative, scheduling, and staffing problems. Often, some of these ocurses are taken concurrently at the senior level.

Two semesters (or two quarters) generally do not provide sufficient elapsed time to carry the design project into the detail design stage because of delays in obtaining materials, information from suppliers, and other guidance.

To be most useful in the successful teaching of design, it would be desirable that the student have sufficient articulation among the design courses so that a significant design project can be carried as far into the systems engineering planning and design phases as is practicable. This means that the design project should extend over a longer period of time. It is recognized that there would be shcduling problems involved, but it is not believed that these are insurmountable.

A desired sequence might be as follows. The students entering the upper division design sequence would have been prepared by having taken as prerequisites the introductory computer, probability, and introduction to design courses plus the analytic courses which make up the mathematics and science stems and the early humanities courses. Students would then take the upper decision design course in the junior year. The class would study the design process in greater detail and would concentrate on performing the Concept Formulation and System Definition activities which make up the Planning Period. They would then select the projects which they would continue to work on in the succeeding courses and would organize into smaller project groups.

Economic Decision Theory would be taken concurrently or following the design course. The class would learn the methodology of economic decision and value theory and apply this to

Table 21. Model Systems Engineering Curriculum (Undergraduate) Proposed by Wymore

	Semester Hours
Required by the University:	12
Composition	
Physical Education	
Mathematics:	32
The Real Numbers	
Algebraic Structure	
Point Set Topology	
Linear Topological Spaces	
Measure and Integration	
Numerical Analysis	
Mathematical Statistics	
Classical Engineering Sciences:	32
Calculus, Analog Computing	
Mechanics	
Electricity and Magnetism	
Optics, Acoustics, and Heat	
Structure of Matter	
Circuits and Electronics	
Fluids and Thermo	
Behavioral Sciences:	32
Chemistry	
Biology	
Psychology	
Anthropology	
Sociology	
Economics	
System Theory:	32
Discrete Systems, Digital Computing	
Continuous Systems	
Optimization	
Probabilistic Systems	
BIGOPS	
Total Units	140

structuring the cost-benefit evaluation criteria for their design projects developed in the design course. It would be even more valuable to have separate quarter courses in engineering economics and in decision and value theory so that deeper penetration may be made into these subject areas.

The design laboratory course would extend over a minimum of three quarters. The laboratory time would build on the work done in the previous courses and would allow substantial penetration into the Detail Design Stage. This means that, for all practical purposes, the students would have from one and one-half to two years, including the vacation quarter, in which to concentrate on a single design project.

The student having gone through such a sequence would have served essentially the equivalent of an internship and would be well prepared, upon graduation, to enter his professional career."

Another model curriculum of systems engineering at the undergraduate level was proposed by Wymore, who identifies six core areas of such a curricula, namely [49]:

1. engineering sciences (classical),
2. probability and statistics,
3. computer science, including analog programming, digital programming, and numerical analysis,
4. operations research, including optimization techniques,
5. system theory,
6. human factors, including the man/machine, man/man, and system/society interface.

Each of these areas is represented by a set of courses in the proposed undergraduate curriculum as shown in Table 21.

Proceeding to the graduate level, we shall describe here briefly the programs offered by the Polytechnic Institute of Brooklyn.

The course requirements for the degree of Master of Science in Systems Engineering are shown in Table 22. As we see, project or thesis (SA 950-951) is optional in the sense that it is part of major S.E. electives. The discretionary power as to whether a project is included in each approved program rests with the department graduate advisor and the student's individual advisor in consultation with the student.

The Institute also offers the degree of Doctor of Philosophy in Systems Engineering. The course requirements of the Ph.D. program contain a minimum of 48 semester hours of course work plus a minimum of 24 credits of doctoral research beyond the Bachelor's degree. The required course credits may be taken at the Polytechnic Institute or elsewhere, and up to 18 credits for the Ph.D. may be obtained by the

Table 22. Degree Requirements: Master of Science (Systems Engineering)
Polytechnic Institute of Brooklyn

A)	**Required Courses**		0-3 courses*
1)	SA 601	Digital Computer Methodology	
	SA 603	Introduction to Linear Dynamical Systems	
	SA 604	Introduction to Feedback Control Systems	
	SA 623	Applied Statistics for Engineers	
	SA 627	Operations Research Models and Techniques I	
	MA 153	Linear Algebra (Graduate Credit Allowed)	
2)	Probability (MA 851 or EE 701)		1 course
3)	Math elective (Statistics, numerical analysis, transform calculus, ordinary or partial differential equations, probability, or stochastic processes)		1 course
B)	**Major S.E. Electives** (2 required)		2 courses
	SA 642	Control Systems I (Also listed as EE 642)	
	SA 643	System Studies in Control (New Course)	
	SA 705	Engineering of Instrumentation for Societal Systems (New Course)	
	SA 711	System Modeling and Analysis I	
	SA 712	System Modeling and Analysis II	
	SA 741	System Studies in Transportation (New Course)	
	SA 743	System Studies in Bioengineering (New Course)	
	SA 950-51	OR&SA Project	
C)	**Other Relevant Electives**		8-11 courses
		Total:	15 Courses

*All of these courses are required, but credit will be granted for no more than 3 of them.

Table 22. (continued)

In selecting the courses for the Ph.D. program, the suggested areas of concentration are the following problem areas:

Bioengineering,
Chemical Engineering,
Control Theory,
Digital Computers,
Economic Analysis & Forecasting,
Mathematical Analysis,
Operations Research,
Transportation Planning,
System Analysis Techniques,
Environmental Engineering,
Urban Government Operations,
Production Analysis, Design & Control,
Planning & Economic Analysis,
Management Information Systems,
Industrial Management.

validation procedure described in the Institute's catalogue.

The qualifying examination consists of two written parts and an oral part. The first written part is common to both System Engineering and Operations Research programs and stresses fundamentals; the second written part is different for the two programs, and covers more advanced and specialized material.

A list of topics in Systems Engineering normally to be expected on the written parts of the examination, together with an indication of texts which would provide normal preparation is shown below:

Subject	Suggested Reference
State Variable Modeling	Seely, Dynamic Systems Analysis
Control Systems (Classical)	Gupta/Hasdorff, Fund. of Aut. Control
Modern Control Theory	Takahashi/Rabins/Auslander, Control
Stochastic Systems	Parzen, Stochastic Processes
Signal Processing	Schwartz, Info. Trans. Modul. & Noise
Nonlinear Systems	Gibson, Nonlinear System Anal.
Modeling & Simulation	Chestnut, System Engrg. Tools
Transform Methods	Churchill, Operational Math.
Distributed Parameter Systems	Alexander/Bailey, Syst. Engrg. Math., Ch. 2
Optimization Techniques	Pierre, Optimization Theory w. Applic.

Eldin, who made a survey of systems curricula and collected comments from the respondents as to what should be the basic ingredients of such curricula, summarized the comments of the respondents as follows [15]:

> "The curriculum built around systems concepts must provide the engineer with sound foundations in computer technology and in the application of management science techniques to the solution of industrial problems. To qualify for systems work, the modern engineer should acquire a developing methodology: an organized approach to handle entire systems. In addition, he should acquire adequate knowledge of available systems tools and techniques. He does not have to be a specialist in depth in these techniques, but he does have to know what it is reasonable to do in various fields from which he will draw parts of the solution. The suggested curriculum is divided into two parts: methodology and tools and techniques.
>
> Part 1 - *Systems Methodology*. This covers the following subjects: The Systems Function, Systems Development Cycle, Systems Analysis and Design, Control System Theory, Feasibility and Trade-off Studies, Operating Procedures and Speci-

fications, Systems Effectiveness and Evaluation, Reliability Engineering, and Computers and Information Systems.

Part 2 - *Systems Tools and Techniques.* There are many tools and techniques about which a systems man should have knowledge. He must know when and where to apply them in the systems process. These may be categorized as follows:

(a) *Mathematical probability, and statistical tools.* The systems man makes extensive use of probability and mathematical statistics. The theory of probability, Bayes' theorem, distributions, and statistics are used in applications concerned with the decision theory and decision making under certainty, risk, and uncertainty. Forecasting techniques owe achievements to exponential smoothing and mathematical regression.

(b) *Computing tools.* Successful application of computers in processing data and supplying results is usually economical and essential in accomplishing the systems effort. Besides being able to understand the potential of the computer and to recognize its applicability to his projects, the systems man should also be able to communicate effectively with computer specialists.

(c) *Modeling, simulation and optimization tools.* Mathematical modeling and simulation are powerful tools for systems work. The key is to identify the problem in form and content. Methods of solution such as analytical, enumeration, and deterministic methods of solution are secondary to problem definitions. Also, characteristics of the mathematical model - whether it is deterministic or stochastic, linear or non-linear, static or dynamic - should be decided upon after thorough investigation of the problem form. Simulation techniques are very powerful in handling queuing problems. PERT, CPM, and Project Managemnet are suitable for sequencing problems. Optimization techniques, such as linear programming and dynamic programming, are useful in handling allocation and routing problems. Value analysis and decision theory are used in selecting from among alternatives in replacement and inventory problems."

In terms of extension of systems approach to more specialized areas, a strong systems orientation of management science curricula is urged by Murdick and Ross [31]. They proposed a curriculum of two parallel sequences, one intended for systems managers (Sequence A), the other for systems designers (Sequence B).

The areas of emphasis of Sequence A are described as follows:

" . *Macroeconomics.* This should treat not just the usual topics of national income and product, but inquire into potential modifications of the economic system in terms of its objectives. The systems approach and its application to this subject should be introduced.

. *Comparative Economic Systems.* This should be an extension of macroeconomics in showing different systems in

operation throughout the world. The degree of coupling to form larger systems should be examined, and modifications that would yield better, larger systems need to be discussed.

. *Business in the Social-Legal-Political Environment* is a course that is now taught at all the up-to-date business schools at the graduate level at least. A version of this is required at the undergraduate level to provide students with a broad knowledge of the impact of major factors on business operations.

. *Consumer Behavior and Industrial and Institutional Buying*. The operational interface between the environment and the individual business system consists of the buyer on one side and seller (salemen) on the other. Consumer behavior courses are now common at the undergraduate level. Some expansion is required, however, to deal with the behavior of buyers of goods for production of other goods or services. With this course we have narrowed down from the large environmental system to that portion of the system that impinges directly and most vitally on the business firm.

. *Business Policy, Strategy, and Long Range Planning*. This course should deal with the goal setting and performance requirements for the business system. The examination of alternative policies and strategies should be made in terms of seeking a viable ecological niche. The nature of conflict and strategies for dealing with conflict would be covered. Finally, timely adaptation is a necessity for growth and survival, and hence long-range forecasting and systematic planning are key topics.

. *Operational Systems*. Operational systems are the subsystems into which the firm is divided for effective communication and decision making. A fresh look at alternatives to the current functional subsystems is greatly needed. This course should deal with the structure of the business system as a whole from the viewpoints of process, operation, communication and decision making. The basic policies, goals and total system requirements should be the only constraints.

In essence, operational systems consist of activities that implement on a short-range and day-to-day basis the immediate goals of the firm. Some modern courses called "operations management" treat these activities, but they still employ the old functional distinctions.

. *Organizational Behavior*. An understanding of the parts of the system and their interractions is required for those who design and operate such systems. Students should therefore study the research results available in organizational behavior. Models of organizations and the organization as a system should provide the framework for this course.

. *Management Information Systems*. The physical system must be controlled primarily by an information, decision-making, learning system. For the business firm, this cybernetic system is presently called the "management information system".

. *Venture Management and Entrepreneurship.* The practical aspects of innovation and risk in new product planning, development and launching would be examined. Venture management and entrepreneurship represent means by which the business system adapts to its environment. These activities represent the short-range flexibility built into long-range plans. They are based upon information about the environment and learning for adaptation."

Sequence B covers the nature and tools of scientific inquiry as follows:

" . *Science, Research and Communication.* The prupose and methods of science, the nature of evidence and the meaning of research would be covered. About half the course would be devoted to developing the student's skill in communicating at various technical levels through different media. Written (text), oral, and graphic communication would receive great attention.

. *Computer Science.* Topics covered would include the basic components of computers, computer logic, capabilities and limitations of the current computer generation, structure of computer languages and man-machine interface problems, and use of the computer for system simulation.

. *Probability and Statistics.* Present modern courses typify this course.

. *Finite Mathematics With Business Application.* A wide variety of topics from a plausibility and application perspective are covered in a number of standard texts.

. *Calculus With Business Applications.* Selected topics in calculus developed from a plausibility and application perspective would be covered.

. *Modeling and Simulation.* Combined application of quantitative techniques and computer science to business system problems."

A summary of the proposed undergraduate curriculum with the recommended degree of proficiency in the subject areas is given in Table 23.

Finally, for students to be educated in socio-economic systems, the following areas are recommended as engineering contribution to the core of the curriculum.

Mathematics and Statistics. Owing to the stochastic nature of most socio-economic systems, a greater emphasis should undoubtedly be placed on probability and statistics than is the case in most engineering curricula.

Basic social theory including economics, sociology, political science, and psychology. This theory can be viewed as parallel to the physics and chemistry of the engineering curriculum. While some knowledge of physical science is undoubtedly necessary, a much larger emphasis must be placed on sound social science (a generic term encompassing the four above mentioned areas).

Table 23. Undergraduate Core Curriculum and Learning Levels in Management Science

M - Management students S - Systems and management science students	Knowledge	Understanding	Skill in Application	Analysis and Evaluation	Synthesis
Sequence A					
1. Macroeconomics		M,S			
2. Comparative economic systems	M,S				
3. Business in the social-legal-political environment		M,S			
4. Consumer behavior, and industrial and institutional buying		M,S			
5. Business policy, strategy, and long-range planning			S	M	
6. Operational systems				M,S	
7. Organizational behavior		M,S			
8. Management information systems		M			S
9. Venture management and entrepreneurship		M,S			
Sequence B					
1. Science, research, and communication			M,S		
2. Computer science			M,S		
3. Probability and statistics			M,S		
4. Finite math with business applications		M	S		
5. Calculus with business applications		M	S		
6. Modeling and simulation		M			S

Wherever possible, this treatment should be from a quantitative point of view.

System Theory. In addition to the theory dealing with systems that can be studied in macroscopic terms, the background of the student in these areas should include a fundamental grounding in probabilistic models, including, in particular, basic Markov processes, elements of decision theory, queuing theory, and the application of these concepts to discrete particle flows.

Larger-Scale System Methodology. In addition to the methodology for approaching large-scale system problems in an orderly manner, the student must acquire the intangible, but nevertheless significant, problem-solving orientation and the experience and motivation necessary to apply the methodology.

Laboratory Experience. Finally, the program of education must include experiences on the part of the student in applying the theoretical concepts, i.e., the socio-economic counterpart of the engineering laboratory. The "laboratory" in this case is the world about us or limited aspects thereof, and it is not possible to isolate the components of the system on a laboratory table and subject them to controlled experiments. Notwithstanding, a framework must be created in educational institutions wherein students at both the undergraduate and graduate levels can become personally involved in at least some of the measurement and survey techniques, the data-processing procedures, analyses, and other specifics involved in actually developing and validating models of real world situations [26].

In concluding this section, few words are to be said about certain general criteria for the design and evaluation of systems engineering science and engineering curricula. If any profession were asked to identify the significant educational programs and criteria for the design and evaluation of such programs, it is likely that the kinds of concerns reflected in the questions and the kinds of criteria proposed would be similar despite the differences in the professions. The following is a list of topics of concern to all professional education:

1. Are there principles in the organization and offering of a curriculum that are especially relevant for professional education?
2. How may a curriculum be accommodated to students with major individual differences and backgrounds?
3. What assumptions can be made concerning expectations that "the student" participate in and take responsibility for his own education?
4. A related question: Can the so-called newer methods of teaching and learning, especially those putting a premium on self-instruction, be adapted to professional education?

5. In what ways can a professional school help the student in the process of career planning?
6. Can advanced students participate effectively in educational programs for younger students? How may they best be used in professional schools?
7. What kind of a formal and informal scheme can be devised to evaluate whether the curriculum objectives have been achieved both for all students and for each individual? [21].

Relatively little has been done to study the above questions systematically with respect to educational curricula in general and system engineering curriula in particular.

4.4 Scope and Orientation of Individual Systems Programs

The scope and orientation of most of the Systems Engineering or Systems Science programs, offered by academic institutions in the United States, are briefly described below. The information regarding those programs was obtained from the catalogues of these institutions, correspondence and site visits. The coverage is not complete because for some institutions there was not enough information available to describe the programs in some detail. The descriptions concentrate on the orientation of system programs, educational philosophy, and program requirements.

University of Arizona.

The Systems Engineering Department offers Bachelor of Science degree in engineering mathematics, and Master of Science and Doctor of Philosophy degrees in systems engineering. Emphasis in the program is placed on a generalized approach to engineering in which the similarities between various technologies are stressed. By studying the basic principles, in particular mathematical modeling and mathematics, the systems engineer is capable of dealing effectively with problems arising from different areas of engineering.

The core of the curriculum consists of engineering science, probability and statistics, operations research, computer science, human factors, and systems theory.

The undergraduate program stresses the generality and broad applicability of course work material thus placing the graduate in an advantageous position in a rapidly evolving technical environment. The graduate program stresses research in interdisciplinary as well as totally new areas and although it is noted that undergraduate study in engineering or mathematics provides a good background for systems, the program is open to students in other specialities. In both the undergraduate and graduate programs, computer science plays an important role.

Polytechnic Institute of Brooklyn.

The undergraduate program in system engineering leads to the degree of Bachelor of Science (System Engineering); it is built around the core of courses that deal with the essential scientific foundations

underlying the field. These courses cover, in an interdisciplinary manner, the viewpoints, tools of analysis, and mathematical techniques of feedback control, instrumentation and measurement, analysis of data, optimization, and the communication of information, stressing the use of analog and digital computers where applicable.

The graduate program is open to students with undergraduate degrees in engineering, mathematics, science, or related fields, and leads to the degree of Master of Science (Systems Engineering) and Doctor of Philosophy (Systems Engineering). The Program is designed to provide a broad background in modern applied mathematics and engineering. The program is intended to train graduate engineers in the analysis and design of large scale systems by the integrated utilization of multiple engineering disciplines.

University of California, Los Angeles.

The Department of System Science at UCLA offers undergraduate and graduate instruction in areas of Automata and Formal Languages, Communication Systems and Information Theory, Control Systems and Optimal Control Theory, Mathematical Theory of Systems, Queuing Systems and Network Flows, System Theory and Optimization. The academic program of the Department emphasizes fundamental concepts and modern theoretical foundations as well as computational and experimental aspects and research aimed at specific areas of application.

Carnegie Institute of Technology.

The Department of Electrical Engineering offers system programs for both undergraduate level and graduate level. The emphasis of the undergraduate system program is placed on the application of linear systems and signal theory to modern communication and control system problems. The purpose of a graduate program is to prepare students for careers leading to leadership in research, development and design in universities, government service, or industries in which electrical and related sciences play a significant role.

Case Western Reserve University.

Case offers Masters and Ph.D. programs in Computer, Control, and Systems Sciences and Engineering. There is a great deal of freedom for interdisciplinary activity, students and professors being free to work with people and facilities outside their department. Much thesis

work is done in connection with the Systems Research Center.

Cornell University.

Department of Operations Research offers a graduate program in Systems Analysis and Design. Emphasis of the program is on analyzing and modeling systems in industry, environmental control, commerce, and government. Research areas include development of new methodologies, and design of complex systems.

University of Florida.

The Industrial and Systems Engineering department offers undergraduate and graduate programs in systems engineering which emphasize the integration of knowledge and technology from the engineering, biological, and physical sciences to carry out the processes of description, analysis, synthesis, and optimization in both the industrial and non-industrial setting. A systems engineer learns to define problems from a broad perspective in which the contributions of individual components to a total mission is clearly seen. The programs draw mainly on economics, operations research, statistics, mathematics, and engineering analysis, with dependence on the computer.

The Department of Industrial and Systems Engineering also offers degrees of Engineer and Ph.D. with a major in Systems Engineering (Operations Research). In order to direct the student toward a realistic self-assessment of his research interests and capabilities, each Ph.D. student is required to prepare himself in a common core area consisting of specified courses in statistics, mathematics, optimization principles and methods, systems analysis, stochastic processes, and digital computer technology.

Georgia Institute of Technology.

The study of Industrial and Systems Engineering places emphasis upon developing the student's abilities to analyze and design systems which integrate technical, economic and social-behavioral factors both in industrial and in various service, social, and governmental organizations. The Systems Engineering program is administered by the School of Industrial and Systems Engineering in conjunction with a campus-wide Committee which advises on interrelationship between systems engineering and other engineering programs. It is an inter-

disciplinary activity dealing with systems implications of engineering, and may be elected as a planned option to supplement and complement curricula in any of the engineering schools.

University of Illinois at Chicago Circle.

The Department of Systems Engineering at the University of Illinois, which is one of four functional departments within the College of Engineering, is concerned with the scientific theory and methodology that is common to all large collections of interacting functional units that together achieve a defined purpose. There are five areas of concentration within the undergraduate program which are associated primarily with the Department of Systems Engineering: (1) Industrial Engineering, (2) Operations Research, (3) Systems Analysis, (4) Transportation Systems Analysis, (5) Transportation Systems Engineering, and (6) Urban Systems Engineering. Thus systems engineering is viewed as the common area of the above specialties, all of which are concerned with complex systems.

University of Miami.

The curricula in Industrial Engineering and Systems Analysis are devoted to education and research in the analysis, design and control of complex technological-sociological systems. A strong emphasis is placed on the applications of modern scientific and mathematical mehtodology and the computer sciences to the problem of obtaining the most effective utilization of the limited resources (men, materials, equipment and facilities) available as inputs to or components of the system. Emphasis is further placed on the consideration of the overall system under study from the viewpoint of its goals, the alternative means of achieving these goals, and finally, the quantitative evaluation of the effectiveness of the proposed alternatives. Examples of areas in which systems of special interest occur are manufacturing and commercial industries, urban government, law enforcement, transportation, education, and medical services.

The Systems Analysis curriculum is designed to afford the student the opportunity to develop an understanding of systems analysis and an ability to apply it to real problems. Stress is placed on providing

a solid foundation as well as an incentive for further study, while permitting the student maximum flexibility to direct his program according to his interests and abilities. The curriculum reflects the multidisciplinary nature of systems problems. Courses are required in humanities, economics, psychology, social science, philosophy, and history or government, to complement the technical training in systems analysis, operations research, statistics, computer sciences, mathematics, and science.

Graduate study is offered in the Industrial Engineering Department leading to a Master of Science degree. Areas of specialization available are: operations research and systems analysis, computer science, human factors, and applied statistics. The individual student is offered much flexibility in organizing a program of study and research in each of these areas. Programs are also available in the interdisciplinary fields of ocean engineering and biomedical engineering, and are administered with the cooperation of the Institute of Marine Sciences and the Medical School.

Miami University.

The program leading to the Bachelor of Science in Applied Science degree with a concentration in Systems Analysis at Miami University at Oxford, Ohio, is predominantly a computer science program. It has as its purpose to prepare students to enter the field of computing and data processing. After the first two years in which all students take basic courses in physical and biological sciences, humanities, English, and calculus students elect to specialize either in scientific or commercial applications. Those who elect scientific applications take additional mathematics courses and operations research while those electing business applications take accounting, inventory and other business courses. This program can be differentiated from the others by its emphasis on the computer as an object of study rather than a tool in the study of other systems. In other words the computer is the system being studied rather than a computational model of another system.

University of Michigan.

The program in Computer, Information, and Control Engineering is

an interdepartmental degree program administered by the Committee on Computer, Information, and Control Engineering. The program provides instruction at the graduate level in areas of and related to computers, control systems, and information systems. Topics which are covered include digital computers (logic and system design, arithmetic, switching and automata theory, computer graphics), analog and hybrid computation, probability, statistics and stochastic processes, information and coding theory, modulation and detection theory, theory of dynamical systems, feedback control systems, optimal control theory, stability theory, and large scale systems. The degrees offered are: Master of Science in Computer, Information, and Control Engineer, and Doctor of Philosophy in Computer, Information and Control Engineer.

Michigan State University.

The systems program leading to the degrees of Master of Science and Doctor of Philosophy are offered in the field of system science.

The systems graduate program provides coordinated studies in the theoretical foundations of dynamic systems and in the applications to systems problems in engineering, business, marketing, transportation, urban development and other areas. It is intended to be meaningful for both the professional systems scientist and those interested primarily in applications.

State University of New York at Buffalo.

Systems program is offered by Electrical Engineering Department jointly with Mechanical Engineering Department. Courses cover System Analysis, Continuous Control Systems, and Digital Control Systems.

Ohio University.

At Ohio University the program leading to a Bachelor of Science in Industrial and Systems Engineering is similar to programs in the other Engineering departments for the first two years. The last two years of work provide the professional level material including computer-related instruction, necessary for the interdisciplinary activities that are required of the modern industrial or systems engineer. Industrial and systems engineering is stated to be concerned with the design and analysis of integrated systems of men, equipment, and materials. It draws upon knowledge from the mathematical, physical,

and behavioral sciences which, in conjunction with the principles and methods of engineering analysis and design, is used to predict, to design, to control, and to evaluate the performance of complex systems.

The master of science program in industrial and systems engineering is fitted to the goals of the individual student. Course concentrations are available in behavior systems, computer systems, general systems, industrial systems and operations research.

PMC College.

The School of Engineering offers a Master of Engineering degree in Systems Engineering.

The curriculum in systems engineering considers all of the aspects of the engineering of large systems. The managerial decision-making aspect is treated throughout along with the mathematical, dynamic response and control, engineering design, economic and special interest areas. This is accomplished in courses entitled Engineering Mathematics, Systems Engineering and System Theory. Special interest areas are recognized. Characteristic of these areas are courses such as Information Systems, Conversion Systems, Vehicle Systems, Bio-engineering Systems, and Environmental Systems.

The graduate of this program is expected to have the capability of functioning as a system engineering generalist or as a manager of technological or corporate activities.

Princeton University.

The Department of Electrical Engineering offers Information Science and Systems Program as one of three majors of the graduate program. This program is broadly formulated to prepare the student for research and teaching in general areas of systems. Research activities are directed toward communication and control systems, biological systems and models, information theory, networks, learning and adaptive systems, pattern recognition, and random process. The program is quite flexible allowing each student to formulate a program appropriate to his interests and abilities. Currently the research program is oriented toward theoretical work and toward extensive use of digital computers for signal processing and system simulation and optimization.

San Jose State College.

The Department of Industrial and Systems Engineering offers the degree of Master of Science for the purpose of preparing engineers to meet more advanced problems in the industrial engineering profession and to gain depth in its recent challenging trends in the areas of systems design, operations research and man-machine relationships. Courses cover Engineering Economy, Operations Research, Statistics, Human Factors, and Computer Sciences.

Southern Methodist University.

The Department of Systems Engineering is an organizational unit of the Institute of Technology at SMU. The department offers B.S., M.S. in Engineering, and Ph.D. in Systems Engineering. The undergraduate courses in systems engineering stress the foundations of systems analysis and design common to all areas of engineering. The aim is to demonstrate the broad range of application of system concepts. The educational program in systems engineering places particular emphasis upon mathematical techniques for decision making. Major emphasis is placed upon areas such as matrix algebra, linear algebra, probability, and stochastic processes, operational calculus, Boolean algebra, optimization theory, partial differential equations and topology.

Stanford University.

The Department of Engineering-Economic Systems at Stanford University offers graduate programs at the masters, engineer and doctoral level designed to prepare "individuals for careers dealing with the phenomena characteristic of planning, operation, and control of large-scale technological-econmic systems".

The degree of Engineer is considered the minimum qualification for a System Engineer.

Tennessee Technological University.

At Tennessee Tech, a Master of Science degree is offered with a major in Systems Engineering. The courses offered include such courses as System Identification, System Analysis, Advanced Linear Systems, Nonlinear Systems, Optimal Control Design, Discrete Time Systems, Non-Deterministic Systems, and Special Problems and research.

University of Toledo.

Members of the University of Toledo's systems committee, recruited from four engineering departments, serve as advisers for students in systems, direct the systems program, and teach most of the systems courses. The doctoral program in systems engineering shares a common core of courses with three other interdisciplinary areas of concentration: chemical and biological transport, engineering mechanics, and materials science and engineering. In addition, doctoral programs include elective courses and a research project. The program leads to a Ph.D. in engineering science. Students at the master's level may elect a department degree or an interdepartmental degree. Students may have a strong concentration or only a small amount of systems study. Thesis requirements vary in different departments. The popularity and importance of systems concepts and techniques have impact on undergraduate education, though Toledo does not yet have a formal undergraduate curriculum in systems engineering.

Washington University.

The interdepartmental program in Control and Systems Science and Engineering is sponsored by the departments of Electrical, Chemical, and Mechanical and Aerospace Engineering. Presently active research areas include stochastic and deterministic optimal control, learning and adaptive systems, linear systems, game theory, control theory, distributed parameter systems, nonlinear filtering, computational methods, identification and sensitivity studies. The degrees are offered for the Master of Science (both course option and thesis option are available) and the Doctor of Science.

Wright State University.

The Bachelor of Science (in Systems Engineering) and the Master of Science (in Systems Engineering) are open to students in engineering and related fields. Wright State's systems engineering program is directed toward the design of machines, information handling systems, control systems, and other large scale facilities. All M.S. candidates must have or must obtain a knowledge of fundamentals in linear systems, electronics, control theory, and digital computer programming.

4.5 Matching Students' Interest with Systems Program Profiles

This section deals with a statistical method of evaluating student's interest in a particular orientation of systems science and engineering programs expressed by the previously developed program profiles. A Scheffe's paired comparison technique is adopted for the test model and evaluation [39]. Several other statistical methods could be selected for this purpose as well, but Scheffe's paired comparison technique seems to have an advantage of easily quantifying personal preferences which are difficult to express by numerical values.

In setting up a testing scheme for the evaluation of student's interests in systems science or engineering, two types of tests could be considered, depending upon the student's familiarity with the subject area:

(Type 1) A student is not familiar with systems science and engineering, but he might have interests in it. (For instance, a highschool graduate might belong to this type.)

(Type 2) A student has a general idea of systems science and engineering and he is interested in selecting a program which matches his interests in an optimal fashion.

The purpose of this section is to describe a statistical method of evaluating the Type 2 student. The method is then illustrated by an example. Tests for Type 1 students shall not be considered in this study.

Suppose m objects numbered from 1 through m are to be compared. All possible M pairs are formed where $M = \frac{1}{2} \cdot m \cdot (m-1)$. Each pair, say i and j, is presented to 2r judges; to r judges in the order (i,j), and to r in the order (j,i). We adopt a 7-point scoring system in which the judge makes one of the following statements for the presented order (i,j).

scores	judges
(3)	I prefer i to j strongly.
(2)	I prefer i to j moderately.
(1)	I prefer i to j slightly.
(0)	No preference
(-1)	I prefer j to i slightly.
(-2)	I prefer j to i moderately.
(-3)	I prefer j to i strongly.

The response for the k-th judge presented with the pair in the order (i,j) is expressed as x_{ijk} and it is assumed that the response for the reversed order (j,i) is $-x_{jik}$. The mathematical model for this experiment is

$$x_{ijk} = (\alpha_i - \alpha_j) + \gamma_{ij} + \delta_{ij} + e_{ijk}$$

where

α_i : main effect of i

α_j : main effect of j

γ_{ij} : interaction of i and j $(\gamma_{ji} = -\gamma_{ij})$

δ_{ij} : ordered effect $(\delta_{ij} = -\delta_{ji})$

e_{ijk}: normal error

An analysis of variance table is shown in Table 24.

Table 24. Analysis of Variance Table

Sources	SS	d.f.	MS
Main effects	S_α	m-1	
Interaction	S_γ	M-m-1	SS/df
Ordered effects	S_δ	M	
Error	S_e	2M(r-1)	
Total	S_t	2rM	

The SS were derived by Scheffe. The results are as follows.

$$S_\alpha = 2rm \sum_{i=1}^{m} \hat{\alpha}_i^2 = 2rm \sum_{i=1}^{m} \left(\sum_{j=1}^{m} \hat{\pi}_{ij}/m \right)^2$$

$$S_\gamma = 2r \sum_{i<j}\sum \hat{\gamma}_{ij}^2 = 2r \sum_{i<j}\sum (\hat{\pi}_{ij} - \hat{\alpha}_i + \hat{\alpha}_j)^2$$

$$S_\delta = 2r \sum_{i<j}\sum \hat{\delta}_{ij}^2 = 2r \sum_{i<j}\sum \left(\frac{1}{2} (\hat{\mu}_{ij} - \hat{\mu}_{ji})\right)^2$$

$$S_e = \sum_{i}^{m} \sum_{j}^{m} \sum_{k}^{r} (\chi_{ijk} - \hat{\mu}_{ijk})^2$$

$$S_t = \sum_{i}^{m} \sum_{j}^{m} \sum_{k}^{r} \chi_{ijk}^2$$

where

$$\hat{\mu}_{ij} = \sum_{k=1}^{r} x_{ijk}/r \qquad (i \neq j), \qquad \hat{\mu}_{ii} = 0$$

$$\hat{\pi}_{ij} = \frac{1}{2}(\mu_{ij} - \mu_{ji})$$

$$\hat{\alpha}_i = \sum_{j=1}^{m} \hat{\pi}_{ij}/m$$

Suppose now a student wants to identify from a given set of systems science and engineering programs one which is closest to his area of interest in terms of main areas of emphasis and also one which fits best his educational background.

The testing procedure consists of the following two steps.

1) Utilizing Table 25 which lists the twelve core factors defined in terms of significant keywords, factors most closely associated with his interests are determined.

2) An institution whose curriculum puts emphasis on the selected factors is chosen.

These two steps are now described in greater detail.

In step one, let the factors be interpreted as objects of the preceding models and keywords as the representative components of the objects. Student's preference to particular topics are recorded on a questionnaire, a sample of which is shown below.

<u>Illustrative questionnaire</u>

Please indicate your preference on the line below each question.

1. I prefer <u>Simulation</u> to <u>Inventory Systems</u>

   -3 -2 -1 0 1 2 3

2. I prefer <u>Feedback Control System</u> to <u>Hypothesis Test</u>.

   -3 -2 -1 0 1 2 3

3. I prefer . . .

Table 25. Twelve Factors and Associated Significant Keywords

Factors	Keywords
1. Signal Processing	noise, detection, signal, spectra, communicating, filter, forecasting, random, representation,
2. Computer Systems	computer, digital, language, data, processor, simulate, analog,
3. Theory of Switching Circuits and Automata	switch, circuit, sequential, synthesis, network, device, algebra, code,
4. Control Systems	stability, response, control, feedback, state, system, criteria, nonlinear, performance, time,
5. Optimization Theory	optimization, calculus, variance, linear, dynamic, program, principle, technique,
6. Engineering Economy	management, finance, economic, accounting, business, organization, decision, planning, production, cost,
7. Theory of Games and Decision Making	game, theories, theorem, information, markov, problem, stochastic,
8. Statistics and Experimental Design	estimates, hypothesis, test, statistical, distributed, nonparametric, correlating, sample,
9. Organic Systems and Human Engineering	factor, human, design, experimental, biotechnology
10. Computer Systems Design	machine, finite, automata, computability, structure,
11. Numerical Analysis	equation, differential, numerical, integral, matrix, method, value,
12. Production Systems (Planning, Scheduling and Inventory Control).	inventory, maintainability, schedules, policies, model reliability, operational, queue, process, research,

For each question, there is a 7-point scoring scale. Based on the assumptions of the Scheffe's method, each pair (i,j) must be presented 2r times; r of them ought to be presented in the order (i,j) and the remaining r are presented in the order (j,i). In the above illustrative questionnaire, the first question belongs to the pair (2,12) i.e. a comparison between factor 2 (Computer Sys) and factor 12 (Production Sys), and the second belongs to (4,8) i.e. a comparison between factor 4 (Control Sys) and factor 8 (Statistics). Other types of questionnaires might satisfy the assumptions of the Scheffe's method as well.

From the data recorded in the questionnaire, statistics for the evaluation of preference are calculated. A sample of hypothetical results is shown in Table 26. Here we have 12 objects (m=12), and the pair (i,j) is repeated 4 times (2r=8).

Table 26. Sample Data From a Program Preference Testing Experiment.

(i,j)	Frequency of Scores X_{ijk} Equal to							Total Score	$\hat{\mu}_{ij}$	$\hat{\pi}_{ij}$
	-3	-2	-1	0	1	2	3			
(1,2)					1		3	-10	2.500	2.500
(2,1)	2	2						-10	-2.500	
(1,3)					1	3		7	1.750	1.375
(3,1)	2		1				1	-4	-1.000	
(1,4)							4	12	3.000	1.500
(4,1)		2				2		0	0.000	
(10,12)		1				3		4	1.000	1.125
(12,10)	1	1	1		1			-5	-1.250	
(11,12)					1	3		10	2.500	2.000
(12,11)	2		1		1			-6	-1.500	
Totals	73	87	59	50	75	92	87			

A corresponding ANOVA table (Table 27) is derived by using the formula presented previously.

Table 27. ANOVA Table for Sample Data

Sources	SS	df	MS
Main effects	1036.8	11	94.25
Interaction	34.4	55	0.63
Ordered effects	133.2	66	2.02
Error	1429.6	396	3.61
Total	2634.0	528	

The significance of the MS of the main effects and the other MSs are judged by taking the ratio to the error mean square and referring it to the F-table.

The comparisons of main effects α_i may be made as follows: With confidence $1 - \varepsilon$ we may make all M statements about the difference $\alpha_i - \alpha_j$

$$\hat{\alpha}_i - \hat{\alpha}_j - Y_\varepsilon \leq \alpha_i - \alpha_j \leq \hat{\alpha}_i - \hat{\alpha}_j + Y_\varepsilon$$

that is, the probability is $1 - \varepsilon$ that all M statements are true under the assumptions (including normality) of the mathematical model. Y_ε is defined as

$$Y_\varepsilon = q_{1-\varepsilon}\sqrt{\frac{\hat{\sigma}^2}{(2rm)}}$$

where $q_{1-\varepsilon}$: upper ε point of Studentized range of

$$\hat{\sigma}^2 = S_e / [2M\,(r - 1)]$$

As a result of comparisons of main effects, we can extract significant factors α_i .

In the second step of our testing procedure, it is required to choose an institution which offers a curriculum emphasizing the

previously extracted significant factors. For the programs of the institutes analyzed in the preceding sections, Table 15 gives the correlations.in terms of weighted values of factors listed for the curricula of selected institutions. For instance, if the factor 6 and factor 4 are selected as significant factors by the preference test, then by referring to Table 15 Univ. of Pennsylvaniz, M.I.T., and N.Y.U. may be recommended.

In this fashion, one can identify the existing systems science and engineering programs which suit best the objectives, aspirations, and background of entering students.

4.6 Conclusions and Potential Extensions

In absence of a general agreement concerning the "ideal" composition of courses in a characteristic systems science and/or engineering program, a representative sample of such programs was analyzed in depth for potential common trends and characteristic features. The analysis was based solely on catalog descriptions of the courses relevant to the programs. Significant concepts were extracted from these course descriptions and used as the data base for factor analysis of the program. Using this technique, it was possible to identify 12 subjects areas which were most characteristic of those programs. These subject areas can thus be considered as a "core" or "model" curriculum for an educational program in systems science or engineering, reflecting the trends on which the sampled institutions agreed most. It was further demonstrated that individual courses and programs can be evaluated in terms of this core program and ranked by the degree of closeness to this core. The results of this comparison can be meaningfully interpreted as indicative of specific orientations of various systems programs.

It should be emphasized again that the results of the study must not be interpreted as a measure of the quality of individual courses or programs of sampled institutions. Data used for the study consisted primarily of course descriptions, which should be reasonably indicative of what is being taught in a school, but not how well it is being taught, for the latter is essentially determined by the quality of the available faculty. Allowance should also be made for inconsistencies, inaccuracies and variations in course description in catalogs, which might have also affected the analysis.

The significance of the study is that it demonstrates a methodology for a quantitative approach to the analysis and design of systems science and engineering curricula in particular and any academic curricula in general. It is also a pilot study in the sense that the utility of the results can be considerably improved by sharpening the criteria for selecting courses and programs, expanding the data base, and including other significant attributes besides the characteristic concepts extracted from course descriptions.

An immediate application of the analysis results was the development of a technique to match Systems Engineering program profiles to entering students interests and objectives. For this purpose, Sheffe's paired comparison method was used. Although the method is very effective for quantifying personal preferences, it has also certain disadvantages. The main disadvantages are:

1. The number of comparisons to be made is large, i.e., $M = 1/2 \cdot m \cdot (m-1)$, and data is to be complete by assumption. For instance, for 12 objects the number of comparisons is 66. In addition, the replications ought to be taken into accounts. Then at least 132 pairs must be prepared to accomplish the smallest complete testing scheme.

2. The model assumes the existence of ordered effects. Since the Scheffe's method was originally developed for taste-testing of foods and use-testing of hand lotions, the existence of the ordered effects is very significant. The taste or the smell is often misevaluated by changing the order of presenting those objects. However, in the application under consideration here, it is clear that the ordered effects are not so significant as the taste or smell test, because the experimenter and the subject have already some idea of the objects to be presented. Then no matter what the order is, the resulting preference ranking should not be affected.

Other possible statistical testing schemes like one-way factorial design and regression analysis might be considered. However, compared with the Scheff's method those methods have a big disadvantage with respect to the scoring system.

There are also a number of other interesting extensions of the techniques described in this study. For instance, one could identify by this procedure the core programs in a number of disciplines such as operations research, bioengineering, information science, industrial engineering, mathematics, etc., and then measure the degree of overlap of these disciplines with systems science and engineering or among themselves. Another application of the proposed technique can be seen in the modular design of new academic programs which would make best use of institutional resources (faculty, facilities, etc.) to satify the actual educational needs.

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APPENDIX A.

SIGNIFICANT KEYWORDS ASSOCIATED WITH EACH FACTOR

TABLE A-1. SIGNIFICANT KEYWORDS ASSOCIATED WITH FACTOR NO.1 AND THEIR SCORES

Keyword	Score
noise	.72
detection	.69
signal	.63
spectra	.56
communication	.53
filter	.49
forecasting	.38
random	.38
representation	.34

Factor interpretation: Signal processing

TABLE A-2. SIGNIFICANT KEYWORDS ASSOCIATED WITH FACTOR NO. 2 AND THEIR SCORES

Keyword	Score
computer	.71
digital	.61
language	.60
data	.50
processor	.48
simulate	.47
analog	.28

Factor interpretation: Computer Systems

TABLE A-3. SIGNIFICANT KEYWORDS ASSOCIATED WITH FACTOR NO. 3 AND THEIR SCORES

Keyword	Score
switch	.74
circuit	.72
sequential	.49
synthesis	.46
network	.44
device	.37
algebra	.36
code	.35

Factor interpretation: Theory of Switching Circuits and Automata

TABLE A-4. SIGNIFICANT KEYWORDS ASSOCIATED WITH FACTOR NO. 4 AND THEIR SCORES

Keyword	Score
stability	.64
response	.55
control	.51
feedback	.49
state	.44
system	.41
criteria	.37
nonlinear	.35
performance	.33
time	.32

Factor interpretation: Control Systems

TABLE A-5. SIGNIFICANT KEYWORDS ASSOCIATED WITH FACTOR NO. 5 AND THEIR SCORES

Keyword	Score
optimization	.55
calculus	.55
variance	.53
linear	.51
dynamic	.50
program	.49
principle	.39
technique	.29

Factor interpretation: Optimization Theory

TABLE A-6. SIGNIFICANT KEYWORDS ASSOCIATED WITH FACTOR NO. 6 AND THEIR SCORES

Keyword	Score
management	.64
finance	.63
economic	.53
accounting	.51
business	.49
organization	.42
decision	.39
planning	.39
production	.38
cost	.37

Factor interpretation: Engineering Economics

TABLE A-7. SIGNIFICANT KEYWORDS ASSOCIATED WITH FACTOR NO. 7 AND THEIR SCORES

Keyword	Score
game	.47
theories	.41
theorem	.39
information	.35
markov	.33
problem	.31
stochastic	.30

Factor interpretation: Theory of Games and Decision Making

TABLE A-8. SIGNIFICANT KEYWORDS ASSOCIATED WITH FACTOR NO. 9 AND THEIR SCORES

Keyword	Score
estimates	.73
hypothesis	.69
test	.63
statistical	.62
distributed	.46
nonparametric	.39
correlating	.37
sample	.35

Factor interpretation: Statistics and Experimental Design

TABLE A-9. SIGNIFICANT KEYWORDS ASSOCIATED WITH FACTOR NO. 9 AND THEIR SCORES

Keyword	Score
factor	.54
human	.47
design	.44
experimental	.37
biotechnology	.36

Factor interpretation: Organic Systems and Human Engineering

TABLE A-10. SIGNIFICANT KEYWORDS ASSOCIATED WITH FACTOR NO. 10 AND THEIR SCORES

Keyword	Score
machine	.67
finite	.56
automata	.52
computability	.31
structure	.28

Factor interpretation: Computer Systems Design

TABLE A-11. SIGNIFICANT KEYWORDS ASSOCIATED WITH FACTOR NO. 11 AND THEIR SCORES

Keyword	Score
equation	.67
differential	.64
numerical	.56
integral	.54
matrix	.45
method	.39
value	.31

Factor interpretation: Numerical Analysis

TABLE A-12. SIGNIFICANT FACTORS ASSOCIATED WITH FACTOR NO. 12 AND THEIR SCORES

Keyword	Score
inventory	.59
maintainability	.43
schedules	.41
policies	.39
model	.36
reliability	.36
operational	.34
queue	.32
process	.31
research	.30

Factor interpretation: Production Systems (Planning, Scheduling and Inventory Control)

TABLE A-13. SIGNIFICANT KEYWORDS ASSOCIATED WITH FACTOR NO. 13 AND THEIR SCORES

Keyword	Score
physical	.41
transport	.40
graph	.40
application	.39
mathematical	.37
electric	.35
power	.32
flow	.31
engineer	.31
field	.30

Factor interpretation: None proposed

TABLE A-14. SIGNIFICANT KEYWORDS ASSOCIATED WITH FACTOR NO. 14 AND THEIR SCORES

Keyword	Score
transfer	.46
functionals	.46
transformation	.36
modern	.33
relation	.32
probabilistic	.31
discrete	.29

Factor interpretation: None proposed

APPENDIX B.

LISTING OF COURSES BY FACTORS

TABLE B-1. LISTING OF COURSES WHICH SCORED HIGH ON FACTOR NO. 1: SIGNAL PROCESSING

School	Course Title	Code		Score
NY U	Methods of Noise and Random Process Analysis	21	17	6.87
CASE W	Random Signals	13	18	6.33
MIT	Random Signals and Linear Systems	14	09	5.99
MIT	Modulation Theory and Systems	14	14	5.97
U PENN	Statistical Analysis of Stationary Time Series	01	27	5.08
PRINCETON	Theory of Detection and Estimation	17	24	4.46
PRINCETON	Signal Analysis and Communications Systems	17	01	4.25
MIT	Probability Theory and Random Processes	14	15	3.54
BRK POLY	Signal Processing	05	32	3.50
U PENN	Statistical Theory in Communication and Control Circuit	01	01	3.38
MIT	Statistical Theory of Nonlinear Systems	14	10	3.38
MIT	Transmission of Information	14	12	2.87
NY U	Information Theory	21	18	2.84
U PENN	Introduction to Random Processes	01	13	2.81
PRINCETON	Introduction to Communication and Information Theory	17	19	2.41
PRINCETON	Pattern Recognition and Learning Machines	17	25	2.30
PRINCETON	Stochastic Signals and Systems	17	20	2.01
PRINCETON	Encoding and Decoding of Information	17	12	1.96
CASE W	Information Theory	13	10	1.67
PRINCETON	Theoretical and Physical Foundation of Random Processes	17	23	1.62
BOSTON	Stochastic Systems	04	03	1.42
TENN T	Non Deterministic Systems	10	07	1.41
PRINCETON	Information Theory	17	22	1.23
NY U	Random Phenomena in Systems Engineering	21	04	1.22
PRINCETON	Discrete Time Systems	17	21	1.16

TABLE B-2. LISTING OF COURSES WHICH SCORED HIGH ON FACTOR NO. 2: COMPUTER SYSTEMS

School	Course Title	Code		Score
MIT	Management Information Systems	14	32	4.47
BRK POLY	Computer Science	05	35	4.39
MIAMI U	Introduction to Systems Analysis	08	02	4.26
CORNELL	Introduction to Computer Science	18	28	4.12
MIT	Advanced Computer Systems	14	33	3.67
CASE W	Systems Engineering	13	04	3.05
NY U	Advanced Computer Methodology	21	36	2.95
CORNELL	Computer Organization and Programming	18	02	2.91
CORNELL	Information Organization and Retrieval	18	09	2.89
STANFORD	Electronic Computation and Data Processing	19	22	2.87
PRINCETON	Advanced Topics in Digital Computation	17	07	2.87
CORNELL	Digital Systems Simulation	18	52	2.84
U ARIZ	Non-numerical Applications of Digital Computers	02	13	2.81
PRINCETON	Programming Systems and their Implementation	17	11	2.46
NY U	System Simulation	21	40	2.46
U ARIZ	Data Processing	02	10	2.41
CORNELL	Data Processing Systems	18	53	2.27
CORNELL	Computer Languages and Compilers	18	04	2.21
BRK POLY	Computer Techniques	05	30	2.05
U PENN	Introduction to Digital Computer Systems and Devices	01	14	1.92
AF INST	Analysis of Management Information Systems	07	10	1.76
CORNELL	Digital Systems Simulation	18	24	1.69
U PENN	Applications of Digital Computers to Business Systems	01	11	1.67
STANFORD	Data Processing Operations Research	19	27	1.64
U ARIZ	Systems Analysts for Data Processing	02	20	1.63
MIAMI U	Analog and Hybrid Systems	08	06	1.59
NY U	Analog and Digital Computers	21	05	1.46
U ARIZ	Programming Digital Computers	02	11	1.46

TABLE B-2. Continued

School	Course Title	Code		Score
MIT	Introduction to Automatic Computation	14	01	1.44
U PENN	Algebraic Foundations for Computer Sciences	01	32	1.42
CORNELL	Data Processing Systems	18	22	1.38
CASE W	Systems Programming	13	21	1.28
CORNELL	Formal Languages	18	12	1.27
NY U	Digital Computer Systems	21	12	1.21
MIAMI U	Systems and Simulation	08	10	1.19
NY U	Computer Systems	21	56	1.15
NY U	Systems Analysis and Design	21	29	1.15
U PENN	Seminar on Information Retrieval	01	28	1.10
U ARIZ	Fortran	02	01	1.05
NY U	Computer Languages	21	48	1.04

TABLE B-3. LISTING OF COURSES WHICH SCORED HIGH ON FACTOR NO. 3: THEORY OF SWITCHING CIRCUITS AND AUTOMATA

School	Course Title	Code		Score
PRINCETON	Theory of Switching Circuits and Automata	17	04	6.38
U PENN	Swtiching Theory	01	09	5.77
PRINCETON	Introduction to Computer Science	17	8	5.22
U PENN	Digital Computers Engineering Logic	01	06	4.68
PRINCETON	Advanced Topics in Automata and Switching Circuits	07	10	4.34
CASE W	Switching Circuit Theory	13	03	3.96
CASE W	Digital Systems Laboratory	13	02	3.88
CORNELL	Switching Systems	18	25	3.76
U PENN	Seminar in Switching Circuits and Automata	01	15	3.27
NY U	Information Processing Systems	17	13	2.76
PRINCETON	Introduction to Digital Computer Engineering	21	06	2.57
CASE W	Digital Computing Circuits	13	19	2.17
CORNELL	Systems Programming	18	05	1.77
PRINCETON	Digital Devices and Circuits	17	05	1.63
MIT	Advanced Topics in Information Theory	14	13	1.24

TABLE B-4. LISTING OF COURSES WHICH SCORED HIGH ON FACTOR NO. 4: CONTROL SYSTEMS

School	Course Title	Code		Score
NYU	Feedback Control Systems and Servo-mechanisms	21	07	5.49
CASE W	Modeling and Control of Physical Systems	13	25	4.46
MIT	Control System Theory	14	20	4.17
PRINCETON	Introduction to Feedback Control Systems	17	03	4.04
MIT	Nonlinear Dynamical Systems	14	21	3.69
U PENN	Feedback Control Systems	01	04	3.54
BRK POLY	System Science	05	31	3.18
CASE W	Advanced Control Theory	13	12	2.92
NY U	Nonlinear Feedback Control Systems	21	15	2.67
CASE W	The Synthesis of Linear Networks	17	16	2.36
NY U	Advanced Linear Systems	10	03	2.12
PRINCETON	Theory of Control	01	10	2.02
TENN T	Introduction to Systems Theory	13	05	1.88
U PENN	Theory of Control	01	10	2.02
CASE W	Introduction to Systems Theory	13	05	1.88
BRK POLY	Industrial Dynamics	05	18	1.79
BRK POLY	Basic System Analysis	05	33	1.77
CASE W	Mathematical Control Theory	13	08	1.77
UCLA	Stochastic Processes in Linear Control	11	07	1.77
NY U	Statistical Quality Control	21	34	1.65
U ARIZ	Deterministic Systems	02	09	1.47
PRINCETON	Adaptive Systems	17	26	1.47
PRINCETON	Control System Theory	17	17	1.21
BOSTON	Advanced Control Theory	04	02	1.20

TABLE B-5. LISTING OF COURSES WHICH SCORED HIGH ON FACTOR NO. 5: OPTIMIZATION THEORY

School	Course Title	Code		Score
NY U	Theory of Optimal Control Systems	21	16	4.62
PRINCETON	Theory of Optimal Control	17	18	4.06
HARVARD	Mathematical Programming & Economic Analysis	20	03	3.82
U PENN	Theory of Optimization	01	16	3.90
CASE W	Systems Optimization	13	11	3.56
U PITTS	Dynamic Systems	22	20	3.48
TENN T	Optimal Control Design	10	04	3.13
BOSTON	Optimization Theory	04	01	2.73
MIT	Theory of Optimal Control	14	25	2.71
STANFOED	System Optimization	19	09	2.63
STANFORD	Mathematical Programming	19	08	2.39
HARVARD	Mathematical Approach to Microeconomic Theory	20	02	2.29
J HOPKINS	Linear and Nonlinear Programming	12	10	2.27
CORNELL	Mathematical Programming	18	37	2.00
U PENN	Adaptive Control Processes	01	19	1.89
UCLA	Stochastic Processes in Linear Systems	11	07	1.77
U ARIZ	Design Optimization	02	08	1.74
CORNELL	Numerical Analysis of Linear & Nonlinear Equation Systems	18	14	1.47
NY U	Nonlinear and Dynamic Programming	21	41	1.24
BRK POLY	Principles of Discrete State Analysis	05	34	1.23
J HOPKINS	Dynamic Programming	12	12	1.16
CASE W	Optimizing and Adaptive Control	13	16	1.15

TABLE B-6. LISTING OF COURSES WHICH SCORED HIGH ON FACTOR NO. 6: ENGINEERING ECONOMICS

School	Course Title	Code		Score
CORNELL	Engineering Economic Analysis	18	40	5.00
UCLA	The Engineer in the Business Environment	11	18	4.96
CORNELL	Advanced Engineering Economic Analysis	18	41	4.75
U PENN	Management Accounting	07	35	4.70
MIAMI U	The Computer in Management Science	8	09	4.43
STANFORD	The Engineering and Organization of Small Businesses	19	32	4.19
U PENN	Industrial Management	01	38	3.97
NY U	Managerial Economic Analysis	21	28	3.81
MIT	Management Information and Control	14	29	3.54
J HOPKINS	Accounting System Models	12	07	3.22
U PENN	Administrative Processes	01	37	3.19
AF INST	Accounting Budgeting and Programming Seminar	07	01	2.99
UCLA	Economics of the Engineering Function	11	09	2.86
AF INST	Economic Analysis	07	12	2.83
U PITTS	Systems Management	22	05	2.77
MIT	Industrial Dynamics	14	34	2.58
UCLA	Synthesis of Engineering Systems	11	01	2.46
STANFORD	Economics of Public Works	19	02	2.41
J HOPKINS	Accounting Systems and Management Decision	12	06	1.99
AF INST	Cost Estimating and Analysis	07	02	1.91
STANFORD	Introduction to Price Theory and Resource Allocation	19	01	1.77
MIT	Advanced Managerial Planning for Information and Control	14	31	1.69
AF INST	Procurement and Production Management	07	08	1.63
AF INST	System Program Management	07	03	1.52
AF INST	Systems Analysis	07	09	1.50
U PENN	Business Economics	01	36	1.42
STANFORD	Capital Budgeting	19	21	1.36
J HOPKINS	Operations Research and Managerial Economics	12	17	1.24

TABLE B-7. LISTING OF COURSES WHICH SCORED HIGH ON FACTOR NO. 7: THEORY OF GAMES AND DECISION MAKING

School	Course Title	Code		Score
U PENN	Programming Languages	01	30	3.84
CORNELL	Introduction to Probability Theory	18	26	3.28
U PITTS	Operations Research	22	02	3.26
U PENN	Theory of Games and Mathematical Programming	01	24	3.16
U PENN	Advanced Probability and Stochastic Processes	01	21	2.85
MIT	Mathematical Behavioral Science	14	28	2.72
HARVARD	Control of Dynamic Systems	20	04	2.62
CASE W	Artificial Intelligence	13	09	2.53
STANFORD	Statistical Decision Theory	09	03	2.15
CASE W	Decision Making and Control in Systems	13	06	2.14
NY U	Systems Engineering	21	19	1.62
J HOPKINS	Theory of Games	12	15	1.57
NY U	Games and Statistical Decision Theory	21	52	1.39
CORNELL	Flow and Scheduling in Networks	18	35	1.38
U ALA	Stochastic Service System	03	10	1.37
PRINCETON	Mathematical Seminar	17	14	1.31
NY U	Elements of Renewal Processes and Markov Chains	21	43	1.23
U ALA	Theory of Reliability	03	27	1.17
PRINCETON	Advanced Topics in Information Processing	17	09	1.17
U NY	Theory of Organization	21	30	1.17

TABLE B-8. LISTING OF COURSES WHICH SCORED HIGH ON FACTOR NO. 8: STATISTICS AND EXPERIMENTAL DESIGN

School	Course Title	Code		Score
U PENN	Statistics	01	23	5.90
CORNELL	Introduction to Statistical Theory	18	27	5.74
J HOPKINS	Introduction to Statistical Theory	12	02	4.99
NY U	Introduction to Reliability and Life Testing	21	46	4.95
NY U	Engineering Statistics	21	23	4.54
U PITTS	Analysis of Variance	22	15	4.39
UCLA	Statistical Design of Engineering Experiments	11	05	4.36
BRK POLY	Industrial Experimentation	05	24	4.00
U PENN	Seminar in Statistics	01	25	3.60
NY U	Correlation and Multivariate Models	21	58	3.51
NY U	Industrial Forecasting	21	27	3.34
STANFORD	Advanced Production Systems Design	19	31	3.23
NY U	Applications of Non Parametric Statistics	21	49	3.05
STANFORD	Queuing Theory	19	28	2.16
CORNELL	Selected Topics in Reliablility and Quality Control	18	45	2.07
HARVARD	Decision Theory	20	01	2.05
AF INST	Research Theories and Techniques	07	11	1.86
CORNELL	Statistical Decision Theory	18	49	1.86
NY U	Optimum Seeking Methods	21	53	1.81
CORNELL	Statistical Methods in Quality and Reliability Control	18	31	1.78
J HOPKINS	Theories of Value and Decision	12	16	1.78
BRK POLY	Acceptance Sampling	05	29	1.32
U PITTS	Experimental Design	22	16	1.29
UCLA	Accepted Topics in Engineering Statistics	11	06	1.27

TABLE B-9. LISTING OF COURSES WHICH SCORED HIGH ON FACTOR NO. 9: ORGANIC SYSTEMS AND HUMAN ENGINEERING

School	Course Title	Code		Score
MIT	Analytical Models for Human Processing of Sensory Inputs	14	17	3.83
NY U	Research Methods in Human Factors	21	33	3.74
U PENN	Seminar in Human Factors Engineering	01	34	3.72
U ALA	Creativity in Engineering Design	03	18	3.70
U ARIZ	Human Factors in Engineering Design	02	05	3.68
UCLA	Advanced Biotechnology	11	11	3.57
NY U	Human Factors in Engineering Design	21	32	3.11
MIT	Bioelectric Signals	14	16	2.95
NY U	Mathematical Models of Human Systems	21	51	2.72
NY U	Information Processing in Man	21	60	2.22
UCLA	Advanced Biotechnology	11	10	2.71
CASE W	Fluid Control Systems	13	13	2.42
STANFORD	Seminar in Man-Machine Systems	19	12	2.32
NY U	Individual Behavior in Industry	21	20	2.09
BOSTON	Advanced Systems Design	04	05	1.96
U PENN	Human Engineering	01	26	1.89
CORNELL	Design of Experiments	18	48	1.87
U ALA	Research Methods in Behavior Systems Eng.	03	16	1.81
NY U	Industrial Experimentation	21	45	1.57
U ALA	Elements of Behavior Systems Engineering	03	15	1.56
J HOPKINS	Design of Experiments	12	08	1.52
BRK POLY	Production Control	05	17	1.49
U ARIZ	Organization Theory	02	16	1.46
U ARIZ	Organic Systems	02	15	1.35
U ARIZ	Bio-engineering Models	02	21	1.35
U ALA	Methods of Experimental Research	03	29	1.32
MIT	Special Studies in Systems Engineering	14	23	1.19
U ALA	Facilities Planning	03	22	1.00

TABLE B-10. LISTING OF COURSES WHICH SCORED HIGH ON FACTOR NO. 10: COMPUTER SYSTEMS DESIGN

School	Course Title	Code		Score
CORNELL	Theory of Automata	18	11	5.79
MIT	Computational Models	14	06	5.27
NY U	Discrete State Machine and Automata	21	11	3.95
MIT	Structure of Computing Systems	14	04	3.82
CORNELL	Automata	18	01	3.47
CASE W	Sequential Machines	13	26	3.25
U PENN	Theory of Automata	01	12	3.22
U ARIZ	Discrete Systems	02	03	3.11
CASE W	Computational Linguistics	13	22	2.89
NY U	Theory of Dicsrete Time Systems	21	14	2.67
U PITTS	Problems in Automata Theory	22	12	2.47
MIT	Electromechanical Components and Systems	14	02	2.41
CORNELL	Theory of Effective Computability	18	13	2.36
U PITTS	Information Engineering	22	10	2.31
CORNELL	Dynamic Programming	18	38	2.23
MIT	Heuristic Programming and Artificial Intelligence	14	08	2.30
U PENN	Continuous Variable Computers	01	05	2.12
U PENN	Mechanical Languages	01	29	2.16
NY U	Queuing	21	54	2.10
CORNELL	Selected Topics in Applied Probability	18	47	1.92
CASE W	Digital Computer Design	13	20	1.86

TABLE B-11. LISTING OF COURSES WHICH SCORED HIGH ON FACTOR NO. 11: NUMERICAL ANALYSIS

School	Course Title	Code		Score
CORNELL	Computer Applications of Numerical Analysis	18	07	5.57
U PENN	Higher Mathematics in the Solution of Engineering Problems	01	17	5.39
U PENN	Numerical Analysis for Computers	01	31	4.98
MIT	Analysis of Dynamical Systems	14	18	4.53
CORNELL	Numerical Solution of Ordinary Differential Equations	18	15	4.05
STANFORD	Analysis of Dynamic Multivariate Systems	19	06	3.96
U PENN	Engineering Techniques for Solving Differential Equations	01	03	3.89
PRINCETON	Linear System Theory	17	15	2.93
U PENN	Nonlinear and Varying-parameter System Analysis	01	08	2.68
U ARIZ	Numerical Analysis	02	14	2.48
UCLA	Analytical Methods in Engineering	11	14	2.43
CORNELL	Numerical Solution of Partial Differential Equations	18	16	2.43
MIT	Process Control	14	24	2.03
MIT	Mathematical Programming	14	35	1.87
STANFORD	Computer Analysis and Simulation	19	10	1.50
U PENN	Seminar on Computers and Computer Complexes	01	18	1.17

TABLE B-12. LISTING OF COURSES WHICH SCORED HIGH ON FACTOR NO. 12: PRODUCTION SYSTEMS (PLANNING, SCHEDULING, AND INVENTORY CONTROL)

School	Course Title	Code		Score
U PITTS	Digital Systems Simulation	22	09	4.82
MIT	Systems Engineering and Operations Research	14	05	4.51
STANFORD	Dynamic Probabilistic Systems	19	07	3.90
CORNELL	Operations Research	18	33	3.53
U PITTS	System Reliability and Maintainability Engineering	22	17	3.37
STANFORD	Planning and Control of Production and Inventory	19	34	3.13
NY U	Production Planning and Control	21	24	2.88
MIT	Case Studies in Quantitative Analysis	14	36	2.87
CORNELL	Production Planning and Control	08	32	2.76
J HOPKINS	Advanced Inventory Systems	02	13	2.74
STANFORD	Models for Production Planning	19	33	2.70
BRK POLY	Operations Research II (Queuing Theory)	05	20	2.68
NY U	Introduction to Operations Research	21	38	2.53
J HOPKINS	Mathematical Methods of Operations Research	12	04	2.49
NY U	Industrial Scheduling	21	26	2.36
NY U	Advanced Reliability and Maintainability	21	47	2.29
BRK POLY	Simulation	05	21	2.15
CORNELL	Queuing Theory	18	43	2.11
AF INST	Supply Management	07	06	2.09
NY U	Linear Programming	21	37	1.98
MIT	Stochastic Systems	14	37	1.83
BOSTON	Systems Design Project	04	06	1.76
CORNELL	Inventory Theory	18	44	1.71
BRK POLY	Production Analysis	05	23	1.38
U ALA	Industrial Engineering Methods	03	14	1.30
BOSTON	Computer Science	04	04	1.25

APPENDIX C.

PROGRAM ORIENTATION: RANKING OF SCHOOLS WITHIN EACH FACTOR

TABLE C-1. INSTITUTIONAL RANKING BY TOTAL SCORE ON FACTOR 1: SIGNAL PROCESSING

1.	M.I.T.	21.75
2.	PRINCETON UNIV.	21.40
3.	UNIV OF PENN.	11.27
4.	NEW YORK UNIV.	10.93
5.	CASE WESTERN	8.0
6.	BROOKLYN POLYT.	3.5
7.	BOSTON UNIV.	1.42
8.	MIAMI UNIV.	1.41

TABLE C-2. INSTITUTIONAL RANKING BY TOTAL SCORE ON FACTOR 2: COMPUTER SYSTEMS

1.	CORNELL UNIV.	23.74
2.	NEW YORK UNIV.	11.42
3.	M.I.T.	9.58
4.	UNIV. OF ARIZONA	9.36
5.	MIAMI UNIV.	7.04
6.	BROOKLYN POLYT.	6.44
7.	UNIV. OF PENN.	6.11
8.	PRINCETON UNIV.	5.59
9.	STANFORD UNIV.	4.51
10.	CASE WESTERN	4.33
11.	AIR FORCE INST.	1.76

TABLE C-3. INSTITUTIONAL RANKING BY TOTAL SCORE ON FACTOR 3: SWITCHING CIRCUITS & AUTOMATA

1.	PRINCETON UNIV.	20.14
2.	UNIV. OF PENN.	13.72
3.	CASE WESTERN	10.01
4.	CORNELL UNIV.	5.53
5.	NEW YORK UNIV.	2.76
6.	M.I.T.	1.24

TABLE C-4. INSTITUTIONAL RANKING BY TOTAL SCORE ON FACTOR 4: CONTROL SYSTEMS

1.	CASE WESTERN	13.88
2.	NEW YORK UNIV.	12.73
3.	PRINCETON UNIV.	9.08
4.	M.I.T.	7.86
5.	BROOKLYN POLYT.	6.74
6.	UNIV. OF PENN.	5.56
7.	TENN. TECH	2.12
8.	U.C.L.A.	1.77
9.	UNIV. OF ARIZONA	1.47
10.	BOSTON UNIV.	1.20

TABLE C-5. INSTITUTIONAL RANKING BY TOTAL SCORE ON FACTOR 5: OPTIMIZATION THEORY

1.	HARVARD UNIV.	6.11
2.	NEW YORK UNIV.	5.86
3.	UNIV. OF PENN.	5.79
4.	STANFORD UNIV.	5.02
5.	CASE WESTERN	4.71
6.	PRINCETON UNIV.	4.06
7.	UNIV. OF PITTSBURGH	3.48
8.	CORNELL UNIV.	3.47
9.	JOHN HOPKINS UNIV.	3.43
10.	TENN. TECH	3.13
11.	BOSTON UNIV.	2.73
12.	M.I.T.	2.71
13.	UNIV. OF ARIZONA	1.74
14.	U.C.L.A.	1.73
15.	BROOKLYN POLYT.	1.23

TABLE C-6. INSTITUTIONAL RANKING BY TOTAL SCORE ON FACTOR 6: ENGINEERING ECONOMICS

1.	UNIV. OF PENN.	13.28
2.	AIR FORCE INS	12.38
3.	U.C.L.A.	10.28
4.	CORNELL UNIV.	9.75
5.	STANFORD UNIV.	9.73
6.	M.I.T.	7.81
7.	JOHN HOPKINS UNIV.	6.45
8.	MIAMI UNIV.	4.43
9.	NEW YORK UNIV.	3.81
10.	UNIV. OF PITTSBURGH	2.77

TABLE C-7. INSTITUTIONAL RANKING BY TOTAL SCORE ON FACTOR 7: GAMES AND DECISION MAKING

1.	UNIV. OF PENN.	9.85
2.	CORNELL UNIV.	5.48
3.	NEW YORK UNIV.	5.41
4.	CASE WESTERN	4.67
5.	UNIV. OF PITTSBURGH	3.26
6.	M.I.T.	2.72
7.	HARVARD UNIV.	2.62
8.	UNIV. OF FLORIDA	2.54
9.	PRINCETON UNIV.	2.48
10.	STANFORD UNIV.	2.15
11.	JOHN HOPKINS UNIV.	1.57

TABLE C-8. INSTITUTIONAL RANKING BY TOTAL SCORE ON FACTOR 8: STATISTICS AND EXPERIMENT DESIGN

1.	NEW YORK UNIV.	21.20
2.	CORNELL UNIV.	11.45
3.	UNIV. OF PENN.	9.50
4.	JOHN HOPKINS UNIV.	6.77
5.	UNIV. OF PITTSBURGH	5.68
6.	U.C.L.A.	5.63
7.	STANFORD UNIV.	5.39
8.	BROOKLYN POLYT.	5.32
9.	HARVARD UNIV.	2.05
10.	AIR FORCE INST.	1.86

TABLE C-9. INSTITUTIONAL RANKING BY TOTAL SCORE ON FACTOR 9: ORGANIC SYSTEMS & HUMAN ENGINEERING

1.	NEW YORK UNIV.	15.45
2.	UNIV. OF FLORIDA	9.39
3.	M.I.T.	7.97
4.	UNIV. OF ARIZONA	7.84
5.	U.C.L.A.	6.28
6.	UNIV. OF PENN.	5.61
7.	CASE WESTERN	2.42
8.	STANFORD UNIV.	2.32
9.	BOSTON UNIV.	1.96
10.	CORNELL UNIV.	1.87
11.	JOHN HOPKINS UNIV.	1.52
12.	BROOKLYN POLYT.	1.49

TABLE C-10. INSTITUTIONAL RANKING BY TOTAL SCORE ON FACTOR 10: COMPUTER SYSTEMS DESIGN

1.	CORNELL UNIV.	15.77
2.	M.I.T.	13.80
3.	NEW YORK UNIV.	8.72
4.	CASE WESTERN	8.00
5.	UNIV. OF PENN.	7.50
6.	UNIV. OF PITTSBURGH	4.78
7.	UNIV. OF ARIZONA	3.11

TABLE C-11. INSTITUTIONAL RANKING BY TOTAL SCORE ON FACTOR 11: NUMERICAL ANALYSIS

1.	UNIV. OF PENN.	18.11
2.	CORNELL UNIV.	12.05
3.	M.I.T.	8.43
4.	STANFORD UNIV.	5.46
5.	PRINCETON UNIV.	2.93
6.	UNIV. OF ARIZONA	2.48
7.	U.C.L.A.	2.43

TABLE C-12. INSTITUTIONAL RANKING BY TOTAL SCORE ON FACTOR 12: PRODUCTION PLANNING & CONTROL

1.	NEW YORK UNIV.	12.04
2.	CORNELL UNIV.	10.11
3.	STANFORD UNIV.	9.73
4.	M.I.T.	9.21
5.	UNIV. OF PITTSBURGH	8.19
6.	BROOKLYN POLYT.	6.21
7.	JOHN HOPKINS UNIV.	4.96
8.	BOSTON UNIV.	3.01
9.	AIR FORCE INST.	2.09
10.	UNIV. OF FLORIDA	1.30

APPENDIX D.

PROGRAM ORIENTATION: RANKING OF FACTORS WITHIN EACH SCHOOL

TABLE D-1. PROGRAM ORIENTATION AT THE UNIVERSITY OF PENNSYLVANIA

Rank	Factor		Weight
1	11	Numerical Analysis	18.11
2	3	Theory of Switching Circuits & Automata	13.72
3	6	Engineering Economics	13.28
4	1	Signal Processing	11.27
5	7	Theory of Games and Decision Making	9.85
6	8	Statistics and Experimental Design	9.50
7	10	Computer Systems Design	7.50
8	2	Computer Systems	6.11
9	5	Optimization Theory	5.79
10	9	Organic Systems and Human Engineering	5.61
11	4	Control Systems	5.56
12	13	Unidentified	2.59
13	14	Unidentified	2.34

TABLE D-2. PROGRAM ORIENTATION AT THE UNIVERSITY OF ARIZONA

Rank	Factor		Weight
1	2	Computer Systems	9.36
2	13	Unidentified	8.36
3	9	Organic Systems and Human Engineering	7.84
4	10	Computer System Design	3.11
5	11	Numerical Analysis	2.48
6	5	Optimization Theory	1.74
7	4	Control Systems	1.47

TABLE D-3. PROGRAM ORIENTATION AT THE UNIVERSITY OF FLORIDA

Rank	Factor		Weight
1	9	Organic Systems and Human Engineering	9.36
2	7	Theory of Games and Decision Making	2.54
3	12	Production Systems	1.30
4	13	Unidentified	1.01

TABLE D-4. PROGRAM ORIENTATION AT BOSTON UNIVERSITY

Rank	Factor		Weight
1	12	Production Systems	3.01
2	5	Optimization Theory	2.73
3	9	Organic Systems and Human Engineering	1.96
4	1	Signal Processing	1.42
5	4	Control Systems	1.20

TABLE D-5. PROGRAM ORIENTATION AT THE POLYTECHNIC INSTITUTE OF BROOKLYN

Rank	Factor		Weight
1	4	Control Systems	6.74
2	2	Computer Systems	6.44
3	12	Production Systems	6.21
4	13	Unidentified	5.41
5	8	Statistics & Experimental Design	5.32
6	14	Unidentified	3.65
7	1	Signal Processing	3.50
8	9	Organic Systems & Human Engineering	1.49
9	5	Optimization Theory	1.23

TABLE D-6. PROGRAM ORIENTATION AT THE AIR FORCE INSTITUTE OF TECHNOLOGY

Rank	Factor		Weight
1	6	Engineering Economics	12.38
2	12	Production Systems	2.09
3	8	Statistics & Experimental Design	1.86
4	2	Computer Systems	1.76
5	14	Unidentified	1.07

TABLE D-7. PROGRAM ORIENTATION AT THE MIAMI UNIVERSITY

Rank	Factor		Weight
1	2	Computer Systems	7.04
2	6	Engineering Economics	4.43

TABLE D-8. PROGRAM ORIENTATION AT THE TENNESSEE TECHNICAL UNIVERSITY

Rank	Factor		Weight
1	5	Optimization Theory	3.13
2	4	Control Systems	2.12
3	14	Unidentified	2.05
4	1	Signal Processing	1.41

TABLE D-9. PROGRAM ORIENTATION AT THE UNIVERSITY OF CALIFORNIA AT LOS ANGELES

Rank	Factor		Weight
1	6	Engineering Economics	10.28
2	9	Organic Systems & Human Engineering	6.28
3	8	Statistics & Experimental Design	5.63
4	11	Numerical Analysis	2.43
5	14	Unidentified	2.19
6	4	Control Systems	1.77
7	5	Optimization Theory	1.73

TABLE D-10. PROGRAM ORIENTATION AT THE JOHN HOPKINS UNIVERSITY

Rank	Factor		Weight
1	8	Statistics & Experimental Design	6.77
2	6	Engineering Economics	6.45
3	12	Production Systems	4.96
4	5	Optimization Theory	3.43
5	13	Unidentified	2.31
6	7	Theory of Games & Decision Making	1.57
7	9	Organic Systems & Human Engineering	1.52

TABLE D-11. PROGRAM ORIENTATION AT THE CASE WESTERN RESERVE UNIVERSITY

Rank	Factor		Weight
1	4	Control Systems	13.88
2	3	Theory of Switching Circuits & Automata	10.01
3	1	Signal Processing	8.00
4	10	Computer Systems Design	8.00
5	5	Optimization Theory	4.71
6	7	Theory of Games & Decision Making	4.67
7	2	Computer Systems	4.33
8	9	Organic Systems & Human Engineering	2.42

TABLE D-12. PROGRAM ORIENTATION AT THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Rank	Factor		Weight
1	1	Signal Processing	21.75
2	10	Computer Systems Design	13.80
3	2	Computer Systems	9.58
4	12	Production Systems	9.21
5	11	Numerical Analysis	8.43
6	9	Organic Systems & Human Engineering	7.97
7	4	Control Systems	7.86
8	6	Engineering Economics	7.81
9	14	Unidentified	4.55
10	13	Unidentified	3.74
11	7	Theory of Games & Decision Making	2.72
12	5	Optimization Theory	2.71
13	3	Theory of Switching Circuits & Automata	1.24

TABLE D-13. PROGRAM ORIENTATION AT THE PRINCETON UNIVERSITY

Rank	Factor		Weight
1	1	Signal Processing	21.40
2	3	Theory of Switching Circuits & Automata	20.14
3	4	Control Systems	9.08
4	2	Computer Systems	5.59
5	5	Optimization Theory	4.06
6	11	Numerical Analysis	2.93
7	7	Theory of Games & Decision Making	2.48

TABLE D-14. PROGRAM ORIENTATION AT THE CORNELL UNIVERSITY

Rank	Factor		Weight
1	2	Computer Systems	23.74
2	10	Computer Systems Design	15.77
3	11	Numerical Analysis	12.05
4	8	Statistics and Experimental Design	11.45
5	12	Production Systems	10.11
6	6	Engineering Economics	9.75
7	3	Theory of Switching Circuits & Automata	5.53
8	7	Theory of Games & Decision Making	5.48
9	9	Otganic Systems & Human Engineering	1.87
10	5	Optimization Theory	3.47
11	13	Unidentified	1.67
12	14	Unidentified	1.60

TABLE D-15. PROGRAM ORIENTATION AT STANFORD UNIVERSITY

Rank	Factor		Weight
1	6	Engineering Economics	9.73
2	12	Production Systems	9.73
3	14	Unidentified	7.45
4	11	Numerical Analysis	5.46
5	8	Statistics & Experimental Design	5.36
6	5	Optimization Theory	5.02
7	2	Computer Systems	4.51
8	13	Unidentified	2.87
9	9	Organic Systems and Human Engineering	2.32
10	7	Theory of Games and Decision Making	2.15

TABLE D-16. PROGRAM ORIENTATION AT HARVARD UNIVERSITY

Rank	Factor		Weight
1	5	Optimization Theory	6.11
2	7	Theory of Games and Decision Making	2.62
3	8	Statistics and Experimental Design	2.05

TABLE D-17. PROGRAM ORIENTATION AT THE UNIVERSITY OF NEW YORK

Rank	Factor		Weight
1	8	Statistics & Experimental Design	21.20
2	14	Unidentified	16.56
3	9	Organic Systems & Human Engineering	15.45
4	4	Control Systems	12.73
5	12	Production Systems	12.04
6	2	Computer Systems	11.42
7	1	Signal Processing	10.93
8	10	Computer Systems Design	8.72
9	13	Unidentified	6.66
10	5	Optimization Theory	5.86
11	7	Theory of Games & Decision Making	5.41
12	6	Engineering Economics	3.81
13	3	Theory of Switching Circuits & Automata	2.76

TABLE D-18. PROGRAM ORIENTATION AT THE UNIVERSITY OF PITTSBURGH

Rank	Factor		Weight
1	12	Production Systems	8.19
2	8	Statistics & Experimental Design	5.68
3	10	Computer Systems Design	4.78
4	5	Optimization Theory	3.48
5	7	Theory of Games & Decision Making	3.26
6	6	Engineering Economics	2.77
7	13	Unidentified	1.52
8	14	Unidentified	1.25

APPENDIX E.

COMPLETE CATALOG DESCRIPTIONS

OF THREE TOP-SCORING COURSES

IN EACH SUBJECT AREA (FACTOR)

FACTOR 1: SIGNAL PROCESSING

NY U Methods of Noise and Random Process Analysis I and II

2 5 3 EE 21 017

Fundamentals of the analysis of random processes with applications to control and communications systems. Elements of probability theory. Random variables and their distributions. Distribution functions. Density functions, and characteristic functions. Stationary and nonstationary random processes. Spectral analysis and correlation functions. Wiener theory of filtering and prediction. Theory of matched filters. Nonlinear filtering. Elements of detection of signals in noise.

CASE W Random Signals

1 S 3 ENG 13 018

Measurement and application of correlation and power density spectra. Linear systems, filtering and prediction. Statistical detection of signals in noise.

MIT Random Signals and Linear Systems

1 S 3 EE 14 009

Combination of a review of methods for the representation and analysis of linear systems with an elementary introduction to probability theory and the problems of characterizing random signals and noise. Specifically intended for first-year graduate students entering from other schools and planning to pursue further studies in the area of random signals including: fundamentals of probability theory, random variables, distributions, averages, characteristic functions, transformation of variables, limit theorems, ensembles and random processes, correlation functions and spectra, elementary detection and decision problems. Topics in the area of linear systems including: convolution and superposition integral. Complex frequency and system function are covered.

FACTOR 2: COMPUTER SYSTEMS

MIT Management Information Systems

1 S 3 MGT 14 032

Introduction to digital computers, and data processing techniques. Emphasis on use of large-scale digital computers in integrated information and decision-making systems, and the technology required to implement them. Topics covered include computer architecture, programming languages, operating systems, data collection, transmission and display, data storage and retrieval, sequential versus random access processing, heuristic techniques, simulation, systems design, analysis and evaluation, cost and value of information, on-line systems, integrated systems and their implementation, military information system, and the role of information systems in an organization. Lectures, library research, programming project, and other exercises.

BRK POLY Computer Science

4 S 3 SYS E 05 035

Signal-flow graphs, their formulation, manipulation and use in analysis, state variables and state graphs, analog simulation of linear, nonlinear and time-varying systems including amplitude and time scaling. Digital simulation and discrete-state system models. Analog-to-digital conversion. Logic elements and logic-circuit design. Computer organization and programming, computer languages of engineering interest. Digital simulation, input and output equipment; interface problems. Use of computers in engineering and scientific research. Non-computational applications of computers, including: computer-aided design, computer graphics: the digital computer as element of real-time control system; hybrid and multi-computer systems. Students will have the opportunity of working on a variety of projects related to the course material. Hybrid computing systems and their application to engineering problems. Time sharing of multi-access data systems. Properties of languages suited to time-shared systems. Special purpose computers, principles underlying design and examples of use.

FACTOR 2: (continued)

MIAMI U Introduction to Systems Analysis

2 S 3 SYS E 08 002

Organization of data and alpha-numerical systems. Flow charting and decision tables, processing equipment-basic processor and storage, data input and output, processing systems. Systems analysis, evaluation, and approaches to design, digital computer programming and processing procedures. Detailed instructions for coding (in symbolic language) the current university computer are given. The symbolic language is used to give more more insight into the actual structure of the computer. Applications are based on the preliminary analyses made in SA 121.

FACTOR 3: THEORY OF SWITCHING CIRCUITS AND AUTOMATA

PRINCETON Theory of Switching Circuits and Automata

1 S 3 EE 17 004

Introductory course in the theory of switching circuits and automata, switching devices, number systems and codes, switching algebra, gate network analysis and synthesis, boolean algebra, combinational circuit minimization, sequential circuit analysis and synthesis-pulse and fundamental mode operation, sequential circuit state minimization, hazards and races.

U PENN Switching Theory

2 S 2 EE 01 009

Study of logical properties of circuits based on two-valued divices used in digital computers and control and telephone switching systems. Elements of logical algebras including the propositional calculus theory of relations, boolean lattices and algebras. Logical analysis and synthesis of combinational nets, optimization of series-parallel controlled contact circuits. Logical analysis and synthesis of systems with internal storage or memory. Optimization of sequential relay circuits.

PRINCETON Introduction to Computer Science

1 S 3 EE 17 008

This course considers the principles of digital computer systems. Topics covered include digital devices and circuits, Boolean algebra, analysis and synthesis of switching networks, finite automata, turing machines, computer organization, arithmetic, memory and control implementation, programming and programming systems.

FACTOR 4: CONTROL SYSTEMS

NY U Feedback Control Systems and Servomechanisms

2 5 3 EE 21 007

Fundamental principles of closed-cycle automatic control systems. Formulation of transfer functions, analysis of closed-cycle control systems and their transient and steady-state response, regulators for voltage, current, speed, temperature, etc.; follow-up systems, electrical and hydro-mechanical servomechnnisms. Root locus methods, frequency response analysis of feedback systems, criteria for stability and methods of starilization. Correlation between frequency response and transient response. Proofs of Routh-Hurwitz and Nyquist criteria for stability. Signal flow diagram Analysts and synthesis of multiloop and multiport systems, carrier systems, introduction to sampled-data systems. Describing function and phase-plane methods of analyzing nonlinear systems.

CASE W Modeling and Control of Physical Systems

1 S 3 ENG 13 025

Static, quasi-static, and dynamic modeling concepts for real and idealized physical processes. Characteristics of spatially discrete and continuous systems, lumped parameter modeling, distributed parameter modeling methods and approximations. Linear operator techniques. State and conjugate variables. Generalized coordinates. Static modeling, sensitivity, dimensional analysis, phenomenological representations, quantitative linearization. Similitude considerations. Quasi-static non-linearities. Lagrangian and Hamiltonian states, n-port and energy flow circuit techniques, bond diagrams. Stability, energy, and state, Time domain and frequency response characterization of systems. Simulation and application to control system analysis and design. Electrical, fluid, mechanical, thermal, biological system.

MIT Control System Theory

1 S 3 EE 14 020

Introduction to basic theory for analysis and design of control systems. Emphasis on linear, infinite time interval problems. Mathematical models for dynamic systems. Review of transforms and stability criteria. Analyses for transient and steady-state response, root loci. Trial-and-error design techniques using frequency response methods. Optimization theory for stochastic and deterministic signals. Selected topics from: Sampled-data theory, analytical tools for stability of nonlinear systems, simulation and computation techniques, sensitivity analysis, and control system components.

FACTOR 5: OPTIMIZATION THEORY

NY U

Theory of Optimal Control Systems

2 5 3 EE 21 016

Consideration of the optimal control problem for deterministic systems with various constraints. Statement of optimal control problem. Review and application of basic techniques from functional analysts and calculus of variations. The maximum principle and dynamic programming, optimal adaptive control. Consideration of the optimal control problem for stochastic systems with various constraints. Optimal design of linear systems with random inputs. Estimation of state variables. Application of stochastic approximations. A stochastic maximum principle. Dual control theory.

PRINCETON

Theory of Optimal Control

1 S 3 EE 17 018

Review of the calculus of variations. Formulation of the optimal control problem. Iterative techniques. Dynamic programming, the maximum principle. Minimum time and minimum fuel systems. Optimal control of discrete systems. Differential games, stochastic optimal control.

HARVARD

Mathematical Programming and Economic Analysis

1 S 3 ENG 20 003

Formulation of mathematical programming problems, duality theory of linear programming; computational methods for linear programming; assignment, sequencing, and combinatorial problems, integerprogramming; decomposition principles; nonlinear programming; Lagrangians, Kuhn-Tucker theorem, gradient techniques, search methods, control of dynamic systems. Review of dynamic systems under deterministic and random inputs. Calculus of variations.

FACTOR 6: ENGINEERING ECONOMICS

CORNELL

Engineering Economic Analysts

1 S 3 OR 18 040

An intensive accelerated survey of financial and managerial accounting and engineering economics. Use of cost information for financial reporting, cost control, and decision making. Specific topics include: theory of double-entry accrual accounting as background for subsequent material; bookkeeping is deemphasized. Use of costs in manufacturing; job order vs. process costing; predetermined overhead rates; standard costs and variances, modification of cost information for decision making; cost dichotomies; profit-volume charts; direct costing; costing of joint products and by-products; economic lot sizes use of costs in other models of operations research. Capital investment planning; the time value of money; use of interest rates; ranking procedures for proposed projects including the MAPI formulas; handling of risk and uncertainty.

UCLA

The Engineer in the Business Environment

3 11 018

Accounting theory, finance, business economics with special reference to their use in and effect on engineering enterprises, organization and management of engineering activity; relationship of engineering function with sales, marketing, production, finance, community, national and international problems. Policies effecting these functions.

CORNELL

Advanced Engineering Economic Analysis

1 S 3 OR 18 041

Analysis topics include: brief review of use of cost information for financial reporting, cost control and decision making, intensive discussion of capital investment planning procedures. Problems in project ranking including use of payoff period, present worth, internal rate of return and MAPI urgency rating. Interdependence of productive investment and financing decision, the cost of capital controversy, handling of risk and uncertainty, applications of linear programming to capital budgeting problems, theory of the firm including objectives, market structure, and pricing policies. Measures of performance, problems of profit measurement in the decentralized firm including intensive discussion of transfer pricing.

FACTOR 7: THEORY OF GAMES AND DECISION MAKING

U PENN

Programming Languages

1 S 2 EE 01 030

First term: intermediate programming theory and practice, definition of languages, algorithms and processors, theory and construction of language translators, compilers, and assembly systems, automatic problem solving; theorem proving and game solving. Meta theorems in problem solving. Use of the ALGOL, LISP, and IPL-V processors on specific problems.
Second term: seminar on programming languages and their interpreters, assemblers and compilers, algebraic, business-oriented, information processing and string-transforming languages.
Either term may be taken independently.

CORNELL

Introduction to Probability Theory

1 S 4 OR 18 026

Theory with engineering applications Definition of probability and basic rules of probability theory. Random variables, probability distributions, and expected values, special distributions important in engineering work and relations among them; elementary limit theorems. Introduction to stochastic processes and markov chains, and their applications in the construction of mathematical models of operation, with emphasis on queuing and inventory models.

U PITTS

Operations Research

1 5 3 IE 22 002

Scientific research concepts in the solution of industrial enginerering problems. The operations research approach in study of a system and formulation of the problem. Basic concepts of inventory analysis and systems simulation, equipment replacement methods, game theory, markov processes, information theory, and system dynamics.

FACTOR 8: STATISTICS AND EXPERIMENTAL DESIGN

U PENN **Statistics**

2 S 2 EE 01 023

Brief review of probability and distribution functions. Point estimation and maximum likelihood estimates. Confidence and tolerance intervals. Theory of testing hypotheses and elements of statistical decision theory. Testing the general linear hypothesis, analysis of variance and covariance. Partial and multiple correlations. Selected topics in multivariate analysis, design of experiments, order statistics and non-parametric inference.

CORNELL **Introduction to Statistical Theory**

1 S 4 OR 18 027

Theory with engineering applications.
The application of statistical theory to problems associated with the analysis of data and inference drawn therefrom. Principles of statistical inference: estimating the value of the unknown parameters of probability distributions, testing hypotheses concerning these parameters; elements of statistical decision theory, introduction to correlation theory and curve fitting by least squares. Applications in regression, statistical control, and experimentation.

J HOPKNS **Introduction to Statistical Theory**

1 S 2 IE 12 002

The elements of mathematical statistics: probability, and probability distributions; expected values and moment generating functions; sampling theory and theories of estimation, tests of hypotheses. The primary purpose of the course is to lay a foundation for the following course in analysis of variance and regression and other specialized courses in statistics.

FACTOR 9: ORGANIC SYSTEMS AND HUMAN ENGINEERING

MIT

Analytical Models for Human Processing of Sensory Inputs

1 S 2 EE 14 017

Processing of sensory inputs (A)
Evaluation and design of research procedures for the simulation of human perceptual processes, review of relevant literature from psychophysics and theory of perception, considering both human perception and the evidence from the study of lower organisms. Application of this information to a critical evaluation of recent work in machine simulation of human perceptual processes. Emphasizing studies of pattern recognition, abstracting, self-organizing systems as perceptual models, etc. Design of experimental research projects utilizing.

NY U

Research Methods in Human Factors

1 5 3 IE 21 033

Experimental and laboratory treatment of selected topics in the area of man-machine systems. Particular emphasis is placed on the experimental investigation of man's information processing capabilities.

U PENN

Seminar in Human Factors Engineering

2 S 2 EE 01 034

Human factors engineering topics which have broad implications to designers of systems and components will be intensively reviewed. Although certain specific readings in the current literature of human engineering will also be assigned, students will be free to select their own topics for individual research. Comprehensive literature searches as well as written and oral reports will be required.

FACTOR 10: COMPUTER SYSTEMS DESIGN

CORNELL Theory of Automata

2 S 4 CS 18 011

Automata theory is the study of abstract computing devices, their classification, structure, and computational power. Topics include finite state automata, regular expressions, decomposition of finite automata and their realization, Turing machines and their computational power. Topics include context-free and context-sensitive languages and their relation to push-down and linearly-bounded automata. Quantitative aspects of Turing machine computations: time and memory bounded computations with applications to language processing and classification of other automata and computations.

MIT Computational Models

2 S 3 EE 14 006

Basic properties and capabilities of finite-state machines, graphical descriptions of machine behavior, experiments for determining internal state or detecting malfunctions. Decomposition of machines into combinations of submachines, regular expression descriptions of machine behavior. Analysis of systems with bi-directional information flow, including information lossless machines. Iterative arrays, and coding schemes, two-dimensional computations, including circuits for performing arithmetic operations. Space-time transformations and synchronization problems.

Basic ways of formulating computational problems, including machine models, functional models, and linguistic models, comparison of these models and their properties, leading to an understanding of computability and decidability. Topics included: non-writing automata push-down store automata, and Turing machines; computers and their relationship to Turing machines; recursive function theory; rewriting algorithms and content-free languages.

NY U Discrete State Machine and Automata

1 5 3 EE 21 011

Analysis and synthesis of finite-state machines, Turing and Universal machines, sequential nets. Theory of machine computations; algorithms, recursive functions, languages, and computability. Threshold networks, probabilistic networks. Machine pattern recognition and cognitive processes.

FACTOR 11: NUMERICAL ANALYSIS

CORNELL Computer Applications of Numerical Analysis

1 S 4 CS 18 007

Modern computational algorithms for the numerical solution of a variety of applied mathematics problems are presented and students solve current representative problems by programming each of these algorithms to be run on the computer. Topics include numerical algorithms for the solution linear systems; finding determinants, inverses, eigenvalues and eigenvectors of matrices; solution of a single polynomial or transcendental equation in one unknown; solution of systems of nonlinear equations; acceleration of convergence; lagrangian interpolation and least squares approximation for functions given by a discrete data set; differentiation and integration; solution of ordinary differential equations; initial value problems for systems of nonlinear first order differential equations, two-point boundary value problems; partial differential equations: finite difference grid technique for the solution of the poisson equation.

U PENN <u>Higher Mathematics in the Solution of Engineering Problems</u>

2 S 3 EE 01 017

Algebraic basis of number systems: Review of sequences, series and integration. Functions of a complex variable and conformal mapping; power series, singular points, residues, branch points and many-valued functions, evaluation of definite integrals of a real variable by method of contour integration, properties of asymtotic expansion and method of steepest decent; special functions : gamma, beta, error, Bessel, Legendre, LaGuerre, Tschebyscheff, Hermite; second order partial differential equations; vector spaces and matrices, eigenvalues, and quadratic forms.

U PENN <u>Numerical Analysis for Computers</u>

2 S 2 EE 01 031

Metric spaces, normed linear spaces, inner product spaces, number and functions approximation, abstract iterative procedures, orthogonal functions and polynomials, equation solving and automatic error analysis, linear equations and matrices, existence theorems for integral and differential equations by iterative methods, finite differences, interpolation, numerical differentiation and integration, guassian quadrature.

FACTOR 12: PRODUCTION SYSTEMS (PLANNING, SCHEDULING AND INVENTORY CONTROL)

U PITTS Digital Systems Simulation

2 5 3 IE 22 009

An introduction to digital systems simulation theory of models, mathematical representation of system activities; design of simulation programs, development of process generations, monte carlo techniques. Significant emphasis on inventory and queuing models. Projects will be concerned with systems analysis via current artificial language processors. An introduction to large scale simulation models of the firm: Bonini model, statistical forecasting methods, e.g., moving average, exponential smoothing, double smoothing, dynamic models of industrial and economic activity. Principles for formulating dynamic system models. Structure of the dynamic system models, equations, symbols, delays, policies, and decisions. Examples of dynamic system models: model of the production - distribution system, dynamic characteristics of a customer-producer-employment system.

MIT Systems Engineering and Operations Research

1 S 3 EE 14 005

Analysis of linear probabilistic systems. Application of linear system theory to the study of finite- and infinite-state, discrete- and continuous-time, stationary and non-stationary, markov and semi-markov processes, optimization of probabilistic systems over short and long time periods by means of dynamic programming. Concurrent presentation of examples in the areas of system reliability, congestion processes, automatic control, maintenance and replacement policies, search procedures, inventory control, and other operating problems of systems, discussion of unsolved problems and promising areas of research.

STANFOED Dynamic Probabilistic Systems

2 Q 3 SYS E 19 007

Analysis of linear probabilistic systems, application of linear system theory to the study of finite- and infinite-state, discrete- and continuous-time, stationary and nonstationary, markov and semi-markov processes. Optimization of probabilistic systems over short and long time periods by means of dynamic programming. A concurrent presentation of examples in the areas of system reliability, marketing, automatic control, maintenance and replacement policies, search procedures, inventory control, and other operating problems of systems.